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Optimization of Nd:Glass Lasers with Phosphate Laser Glass

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In this report the impact of phosphate base neodymium glass on laser design for fusion experiments is examined. It is shown that in an optimum amplifier this glass solves the self-focusing problems for pulses longer than 250 ps. Large systems (> 100 kJ) appear possible with this glass with overall efficiencies on the order of 0.2% for nanosecond pulses. For short pulses this glass gives at least a factor of five improvement over silicate systems in terms of cost per terawatt. Phosphate optimized rod amplifier systems are also examined, and found far less desirable than the disc system, both in cost and complexity.

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Optimization of Nd:Glass Lasers with Phosphate-Laser Glass

1. INTRODUCTION

Neodymium-glass lasers have been the choice for laser-plasma experiments to date both because it is relatively simple to build a neodymium system which will produce high-peak powers (> 100 GW) and because the plasma phenomena observed with such lasers are of interest in the laser-fusion problem.

However, a laser which is capable of achieving breakeven, or net yield from a pellet target will be much larger than those used to date. Present expectations are that the laser output must be 100 - 200 TW with a total pulse energy on the order of at least 10^5 J.

The cost of building multiterawatt lasers with present silicate glasses has been estimated to be on the order of $750,000/TW. This would lead to an expectation that such a large system would cost in the range of 75 - 150 M$. Clearly the premium on laser optimization is large.

Recently several manufacturers have produced phosphate base neodymium laser glasses which appear to offer the promise of much more economical operation than silicate base neodymium laser glasses. In this report we will examine the potential of these glasses for effecting large cost reductions.

In the first section of this report we will examine the present data base on the performance parameters for the phosphate laser glass and then examine the impact of these on intrinsic system efficiency.

In the second section we will examine the expected effect of replacing the silicate glass with phosphate glass in two systems Argus (LLL) and Pharos II (NRL). This will serve both as a check on our general arguments about relative efficiency and will also serve as a guide to the design of real systems.

Note: Manuscript submitted November 4, 1976.

In the third section we will pursue our analysis a step further and look at a phosphate system designed to produce the same output as the twenty (20) beam Shiva system under construction at Lawrence Livermore Laboratory (LLL). Finally, we will address the question of a 100 kJ phosphate system and attempt to estimate its cost relative to the Shiva system.

The conclusion we reach is that the phosphate glass offers the potential for substantial system cost reduction at any pulse duration and a spectacular improvement for subnanosecond pulses.

2. SCALING LAWS AND MATERIALS PARAMETERS

The properties of the different possible host materials can strongly affect the performance of a glass laser. If crystalline hosts are included, the range of values for the induced emission coefficient σ range from about 8×10^{-19} cm^2 (Nd:YAG) to $\sim 1.6 \times 10^{-20}$ cm^2 (early silicate laser glasses such as AO-3889). Values of the nonlinear index of refraction n_2 can range between $\sim 5 \times 10^{-14}$ esu and 4×10^{-13} esu.

Recently, scientists at LLL have made excellent progress in modeling laser glasses, and in predicting the nonlinear index of refraction and induced emission coefficient for a variety of possible host materials.[1,2] This program has provided excellent guidance for the glass companies in evaluating potential materials and has aided selection of those with the greatest potential for improvement. This is of course not the solution to the whole problem of better laser materials; a potentially desirable material may in fact prove impossible to make in pieces of the desired volume with excellent optical quality, or the mechanical properties of the glass may prove to be inadequate for fabrication into a laser system. Numerous examples have occurred in the past where a material with some desirable property failed because of practical difficulties which could not be overcome.

It is, therefore, necessary to understand the scaling laws which will govern efficient laser operation in the regime in which we are interested for laser fusion in order to understand more clearly the impact of the materials parameters on laser capability and cost. Then the emphasis can be given to those materials which have the greatest potential. It is just as necessary to understand how these parameters affect the configuration of possible lasers.

2.1 Scaling Laws

At this point it is not possible to state with precision a unique best pulse width for laser fusion as there are numerous pellet designs, none of which have been experimentally checked at irradiation levels where significant thermonuclear burn was achieved (or would be expected). The two extremal cases would appear to be solid drops of DT and thin

shells of DT. In the former case although the total laser pulse might last tens of nanoseconds, the major fraction of the energy must be delivered in a short very intense pulse (> 10^{14} W in a pulse ~ 100 ps long). For thin shells the pulse duration may be much longer (~ 1 - 10 ns) and the peak power much lower. The energy delivered by the laser may be very large, however, (~ 10^5 J).

It is quite possible that the "best" pellet will be intermediate in its requirements. In any case it is clearly desirable that any large laser installation be as optimum as possible over this range of pulse duration (10^{-10} - 10^{-8} sec). There are two limiting mechanisms which affect our ability to deliver energy from neodymium system. For short pulses, self focusing is the limitation and for the long pulses the limit is materials damage.

To examine the tradeoffs between laser materials in an orderly fashion we will examine how the physical parameters of the laser material affect the performance in these two limiting cases.

To achieve a meaningful comparison of the major cost factors involved in building a large laser it is necessary to use a measure related to the cost. This is not output energy density per unit aperture area but is output energy per unit volume of laser material at fixed pump energy per unit volume to a very good approximation.

Fixed pump energy per unit volume is a reasonable constraint in that for disc amplifiers this is essentially the case; flashlamp life expectancy and flashlamp caused surface damage limit the pumping flux to a level sufficient to give ~ 0.6 J/cc stored for silicate glass for service life of ~ 1000 shots. (The case of rod amplifiers is treated separately in Appendix A; the results are not interesting enough to merit complicating the present line of reasoning.)

Assuming equal pump-energy density per unit volume and then solving for the volume gives a measure closely related to the laser cost since it gives a direct relative comparison from glass to glass of the amount of glass and the size of the capacitor bank flashlamp system required. There are of course other cost factors for a large system, the building, the mounting system, alignment system and targeting system.

The reader is referred to the study of the cost factors for the LLL Shiva design[3] as we will not attempt to analyze all of these factors except to note that approaches which minimize the volume of laser glass for a given output will also tend to minimize the building size and mounting frame. Our relative measure should then give a good comparison of scaling of the major cost factors which account for ~ 80% of the cost of Shiva.

2.1.1 <u>Peak power limited systems</u> - In the case where the desire is for the maximum peak power, the limitation on glass lasers is breakup of the laser beam caused by self focusing of the beam. This process has been intensively studied in the past several years and a number of relevant papers published on the subject.[4,5,6,7] The problem is not the overall collapse of the beam to a small channel; for large beams the threshold intensity would be enormous; rather the beam is much more unstable to higher spatial frequency perturbations, which can collapse in a length shorter than the system size. Suydam has derived a result for the amplification factor as a function of spatial frequency;[5] this theory was found to be in good agreement with an experiment at LLL in which the growth factor was measured.[7] In experiments at NRL, Suydam's extension of the theory to amplifying media was shown to be in agreement with results achieved on amplifiers with differing gain coefficients.[6] The physical picture is that existent spatial noise at some spatial frequency K is amplified by a factor

$$\mu(K) = \exp g(K) . \tag{2.1}$$

For a real system there are many possible sources of spatial noise. Some of these are unavoidable (such as the index inhomogeneity of the laser media). At some value of g(K), the spatial noise will be amplified to an extent that the overall radiance (power density per unit solid angle) will cease to increase as the intensity is increased. That is, there

will be a maximum value of g(K) beyond which the beam quality is destroyed.*

From Suydam's analysis for amplifiers where there is no saturation g(K) will depend on the materials parameters as $K = K_{max}$

$$g(K) = (\text{const.}) \cdot \frac{I_f n_2}{n_o \alpha} , \tag{2.2}$$

where

I_f is the output intensity,

n_2 is the nonlinear index of refraction,

and

α is the gain coefficient.

Given some array of noise sources in a particular laser system and a definition of a tolerable growth factor we can rearrange Eq. (2.2) to yield

$$I_f = \frac{\alpha n_o}{n_2} (\text{const.}) . \tag{2.3}$$

The energy extraction from the laser, E, can be written as

$$E = \frac{\pi D^2}{4} \Delta t \cdot f \cdot (I_f - I_o) , \tag{2.4}$$

where

*The radial variation of beam intensity will cause this level to be reached at different intensities for different radial increments of the beam. Thus, several definitions of the maximum value are possible. At this point we will simply assume the same definition is used as we change materials.

Δt is the pulse width and

f is a factor which accounts for the radial beam profile.

Using Eq. (2.3), the energy extraction from the amplifier for $I_f \gg I_o$

$$E = \frac{\alpha n_o}{n_2} \Delta t f \text{ (const.) } \frac{\pi D^2}{4} . \tag{2.5}$$

The length of laser glass which must be pumped to a gain α to amplify from I_o to I_f is

$$Z = \frac{1}{\alpha} \ell n \left(\frac{I_f}{I_c} \right) . \tag{2.6}$$

The pumping energy E_p will be proportional to $\frac{\pi D^2}{4}$ Z hence the overall extraction efficiency $\mathcal{E}$ will be

$$\boxed{\mathcal{E} = \frac{n_o \alpha^2 \Delta t \text{ (const.)}}{n_2 \ \ell n \ (I_f/I_o)}} . \tag{2.7}$$

Does this "efficiency" represent a cost effectiveness factor? Yes, because at fixed pumping energy per unit length (determined by constraints on flashlamp life-time) higher gain materials will allow shortening of the system length as well as operation at higher intensity. Smaller n_2 values will also be cost effective as they will allow operation at higher intensity which will result in greater extraction efficiency.

2.1.2 Impact of material parameters on beam diameter - In addition to generating short-laser pulses with high efficiency from a minimum volume of laser glass, we are also interested in achieving some net total power

on target. A relevant parameter is the influence of materials parameters on the total power per beam.

Disc amplifiers can be considered almost constant surface area to volume ratio devices; this means that as we increase the size of the discs the size of the flashlamp array increases also such that the flashlamp energy/unit volume of laser glass remains constant. It is, therefore, possible to build large disc amplifiers - up to a point. The upper limit will be given by the constraint that as the disc diameter increases, the net gain across the disc also increases. At some net gain the disc will begin to lase on its own. The discs in use in laser amplifiers are approximately 2:1 aspect ratio ellipses to match a round-beam incident at Brewster's angle. The parasitic mode which generally first exceeds threshold is one which follows a path where it bounces off the disc faces at the critical angle for total internal reflection and also off the periphery of the disc.[8] The threshold condition for this mode is

$$n_o \alpha D_M \geq - \ln R \, , \qquad (2.8)$$

where n_o is the index of refraction of the disc, $D_M \simeq 2\,D$ is the major-axis length of the disc and R is the reflectivity of the periphery of the disc. To minimize the edge reflectivity of the disc a solid or liquid edge coating has been used with an index of refraction slightly above that of the laser glass.[9,10] With silicate-glass values of $\alpha D_M \approx 3.0$ have been achieved[11] and higher values may be possible although superfluorescent depumping would appear to make operation at $\alpha D_M > 4$ very inefficient.[8]

There is another disc-parasitic mode which can lase, and in some cases may lase at lower values of α than the first mode, in which the mode path is straight across the disc. This mode may have appreciable gain near the surface of the disc because the energy deposition in discs is nonuniform and is a maximum near the surface. The threshold condition is

$$\alpha_s D_M \geq - \ln R \, , \qquad (2.9)$$

where α_s is the gain coefficient at the surface of the disc. This mode will have a lower threshold than the bulk mode if $\alpha_s \geq n_o\alpha$. This condition will place a restriction on the neodymium concentration in large disc (large = large values of αD) and this can affect the pumping efficiency. Clearly, parasitic oscillation will limit the diameter of the amplifier beam to a value

$$D \leq -\frac{\ln R}{2\, n_o \alpha} \qquad \text{(Bulk mode)} \quad , \tag{2.10}$$

or

$$D \leq -\frac{\ln R}{2\, \alpha_s} \qquad \text{(Surface mode)} \; , \tag{2.11}$$

whichever is smaller. For the case where the doping is restricted to a value where $\alpha_s \leqq n_o\alpha$, we can use Eq. (2.10) to represent the parasitic constraint.

From Eq. (2.3) the total power/beam can be written as

$$P = \frac{\pi D^2}{4}\, f I_f + \frac{\pi D^2 \alpha n_o}{4\, n_2}\, (\text{const.}) \; . \tag{2.12}$$

By use of Eq. (2.10) we can find the scaling of the total power per beam to be

$$\boxed{P = \frac{1}{n_o n_2 \alpha} \left(\frac{\pi}{4} (-\ln R)^2 \right) \quad (\text{const.})} \quad . \tag{2.13}$$

In evaluating materials in terms of power/beam then, it is necessary to not only consider the product $n_o n_2 \alpha$, but also how well the material can be index matched by parasitic suppression coatings.

2.1.3 Materials damage limited systems - For applications where pulses longer than a nanosecond are required the limitation on laser operation will be damage to optical components, chiefly dielectric coatings rather than self-focusing damage. Bulk damage for most materials will not be a problem until the energy density exceeds a few tens of joules/cm^2, but present coatings cannot be reliably operated in the nanosecond range at peak levels much in excess of 10 J/cm^2 (at normal incidence). This level is in excess of the saturation flux $E_s \equiv h\nu/2\sigma$ for the materials under consideration, so we cannot use the approximation of small signal gain which we used in the earlier short-pulse analysis. We can use the Franz-Nodvik analysis for the performance of a saturable amplifier* to write an equation relating incident and final energy density from an amplifier as[12]

$$\frac{E_f(Z)}{E_s} = \ell n \left[1 - (1 - \exp E_o/E_s) e^{\alpha Z} \right] . \tag{2.14}$$

In this case the output-energy density does not depend on the parameters of the laser glass, but on extrinsic factors, so the overall performance is characterized only by the gain length necessary to amplify a pulse from $\mathcal{E}_o$ to $\mathcal{E}_f$. The cost effectiveness then will scale as Z^{-1} and

$$\boxed{\mathcal{E} = \alpha \left[\ell n \left(e^{E_f/E_s} - 1 \right) - \ell n \left(e^{E_o/E_s} - 1 \right) \right]^{-1} \times (\text{const.})} . \tag{2.15}$$

*We make two simplifying assumptions. First the pulse is short compared to the lower level life-time; hence, it is in effect a three-level amplifier. Second, the loss per cm is much less than the gain per cm. In this case we can ignore the losses and make an ex post facto correction for losses with adequate precision.

2.2 Materials Parameters

In the preceding section we derived expressions for the scaling of the short-pulse efficiency, the power per beam and the nanosecond-pulse efficiency with materials parameters. Parameters of interest are the ordinary and nonlinear indices of refraction n_o and n_2, the induced-emission cross section σ and its inverse the saturation flux ($E_s \equiv h\nu/2\sigma$ for short pulses) and the gain-coefficient α. All but the last parameter are intrinsic properties of neodymium in a particular host material. The gain coefficient, however, represents a combination of properties of the laser glass and the pumping source. The gain coefficient α is defined as

$$\alpha = \sigma N \quad , \tag{2.16}$$

where N is the population inversion between the upper level $({}^4F_{3/2})$ and the lower level $({}^4I_{11/2})$. Several factors can influence the attained value of population inversion in different glasses under identical pumping conditions. The absorption per ion may differ and the quantum efficiency may differ. The degree of concentration quenching of the fluorescence may also vary.

We will consider four laser glasses in this study. An early silicate such as AO-3669 is interesting since it has parameters similar to those reported for the glass used in the large systems under construction at the Lebedev Institute in the USSR. ED-2 is the Owens-Illinois silicate glass, which is in most general use in the West. LHG-5 is a phosphate glass developed by the Hoya glassworks in Japan and Kigre Q-88 is phosphate glass developed by Kigre Inc., Toledo, Ohio.

Table 2.1 summarizes the relevant properties of these glasses. The sources for the information are diverse. The cross-section numbers have been calculated at LLL and in many cases experimentally obtained elsewhere.[18] The n_2 values are generally from calculations and measurements at Livermore with the exception of the AO-3669. That number is

estimated to be the same as for ED-2 based on an experiment in which the relative n_2 values of various glasses were obtained and one sample was of a very similar composition.[14]

Table 2.1 - Comparison of Laser Glasses

Property \ Glass	Early Silicate	ED-2	LHG-5	Q-88
Cross section σ (cm^2) x 10^{20}	1.2	..9	3.9	4.2
$n_o(\lambda_p)$	1.5	1.55	1.53	1.537
$n_2 \times 10^{13}$ (esu)	1.4	1.4	1.16	1.2
Saturation flux $h\nu/2\sigma$ (J/cm^2)	7.8	3.2	2.4	2.24

It is a bit harder to find comparable values for the gain coefficients since this measurement involves a number of materials properties and the parasitic oscillation constraint would argue that we not only need a comparison at equivalent-pumping fluxes but also at equivalent-optical depth in the glasses.

ED-2 is the glass whose properties are most extensively parametrized and we will attempt to estimate the properties of the other glasses relative to ED-2 under the same pump conditions. An estimate for the relative gain coefficient of the early silicate glass to ED-2 is $\alpha_{rel} = .44 \pm .10$. This is consistent with the behavior of similar glasses in the large CGE 30 ns rod systems and is consistent with the beam splitting in the Lebedev Institute 216 beam system.[15] This gain ratio is almost the ratio of the cross sections.

Measurements on LHG-5 vs LSG-91H, the Hoya equivalent to ED-2, have been performed at KMS Fusion[16] and LLL.[17] The phosphate discs were

the same doping as the LSG-91H discs used in these comparisons. At KMS the relative gain value was $\alpha_{rel} = 1.53$ and in the Livermore measurements the value obtained was also $\alpha_{rel} = 1.53$. Use of these raw numbers may tend to overestimate the systems benefit for this glass. If there had been an identical population inversion for the two cases we would expect $\alpha_{rel} = \sigma_p/\sigma_s = 1.35$. This would indicate that the average energy storage was higher by 13%. This may correspond to a similar absorption profile and less concentration quenching, or some fraction of this change may correspond to a higher absorption per ion. In another case the Electrotechnical Instutute (Japan) has reported a specific gain ratio $\alpha_{rel} = 1.90$ for this glass vs LSG-91H.[18] It is possible that in the U.S. experiments the relatively long-pumping pulse duration, 800 ns, handicaped the phosphate glass. Hoya internal tests would appear to give an expected value $\alpha_{rel} = 1.80$.[19] It is worth noting that at both KMS and LLL the gain of LHG-5 was measured at 1.064 and found to be almost identical to the gain of LSG-91H at 1.064.

Several tests have been performed on the gain of Kigre Q-88 phosphate glass. J. Soures (at Rochester) has measured the gain of Q-88 vs LHG-5.[20] It was found to be $\alpha_{rel} = 1.20$ for the two phosphates. More recently at NRL we have measured the gain coefficients of discs of Kigre Q-88 at 1.052 μm, 1.061 μm and 1.064 μm relative to ED-2 at 1.064 μm in the NRL 67 mm aperture disc amplifier.[21]

Extrapolated to 1.054 μm, the NRL measurements gave gains of 17.4%/cm for a 2 wt percent disc and 18.5%/cm for a 3 wt percent disc at a pump energy where a gain of 8%/cm was obtained for a 3% ED-2 disc at 1.064 μm. In this case $\alpha_{rel} = 2.2$ for Q-88 vs ED-2. Interestingly enough, the gain at 1.064 μm for the Q-88 3% disc was found to be 12%/cm, noticably higher than the ED-2 gain at the same wavelength. The cause of this may be the shorter-pumping pulse used in the NRL measurements, 350 μs vs 800 μs in the LLL measurements which would preferentially help the phosphate glass relative to the silicate glass. Discs with 4 and 4.8 wt percent neodymium were tried and the surface mode parasitic was

noted. Table 2.2 compares these various results.

Table 2.2 - Gain Measurements

Glass	α_{rel}(350 μs)	α_{rel}(800 μs)
Old silicate/ED-2	.44	.44
LHG-5/ED-2	1.8	1.53
Q-88/ED-2	2.2	1.75

In summary, there may be an effect of pump duration, such that in the LLL and KMS experiments the LHG phosphate did not show to best advantage. It would appear that a reasonable conclusion is that the 15 - 20% discrepancy between various measurements of the relative gain numbers for phosphate vs silicate is because of two factors:

- differences in pump-pulse duration,
- cerium is used in ED-2 to prevent solarization. This ion masks a neodymium pumpband which is not masked in Q-88 so the Q-88 will perform better at high current density when the lamp radiation is shifted to the blue end of the spectrum.

2.3 Performance Predictions for Various Glasses

We will first look at how these four glasses perform in the short-pulse limit and then examine the long-pulse limit. In the former case the results will be shown to depend on laser-glass parameters while in the latter case, damage thresholds for components strongly affect the figures of merit.

2.3.1 Short-pulse limit - In Sec. 2.1 we derived results for the scaling of short-pulse efficiency and total power per beam. The relevant

results were

$$\mathcal{E} = \frac{n_o \alpha^2}{n_2} \Delta t \quad (\text{const.})^* \quad \text{Eq. } (2.7),$$

and

$$P_T = \frac{1}{n_o n_2 \alpha} \left(\frac{\pi}{4} (- \ln R)^2 \right) \quad (\text{const.}) \qquad \text{Eq. } (2.13).$$

Using Tables 2.1 and 2.2 (first column) we can look at the expected short-pulse performance of these glasses

Early silicate

$$\mathcal{E} = 0.21 \quad \Delta t \ (\text{const.})$$

$$P_T = 1.08 \left(\frac{\pi}{4} (- \ln R)^2 \right) \quad (\text{const.})$$

ED-2 (and LSG-91H)

$$\mathcal{E} = 1.07 \quad \Delta t \ (\text{const.})$$

$$P_T = 0.46 \left(\frac{\pi}{4} (- \ln R)^2 \right) \quad (\text{const.})$$

LHG-5

$$\mathcal{E} = 4.15 \quad \Delta t \ (\text{const.})$$

$$P_T = 0.3 \left(\frac{\pi}{4} (- \ln R)^2 \right) \quad (\text{const.})$$

*We have dropped the term in $\ln \left[I_f / I_o \right]$ here. Typically $I_f/I_o \geq 10^4$. Differences from glass to glass of a factor of two in output power density capability will result in less than a ten percent difference in the comparisons, which is less than the experimental uncertainty on α^2/n_2.

$$\mathcal{E} = 6.2 \quad \Delta t \text{ (const.)}$$

$$P_T = 0.245 \left(\frac{\pi}{4} (- \ln R)^2\right) \quad \text{(const.)}$$

In Fig. 2.1 we can plot cost (proportional to $\mathcal{E}^{-1}$) vs total power per beam.

The tradeoff in cost vs power per beam is much faster than linear. Doubling the number of beams to reach some net total power the total cost of the beams will drop a factor of two to three, which should provide an adequate margin to pay back the extra cost in targeting the extra beams.

2.3.1.1 Fluorophosphates - A reasonable question is how the fluorophosphates will alter the tradeoffs. Parameters of FK-51 fluorophosphate glass have been reported recently.[13] They were $n_0 \approx 1.50$, $n_2 = 8 \times 10^{-14}$ and $\sigma = 2.5 \times 10^{-20}$. If this glass stores energy with 93% of the efficiency of LHG-5, as stated in the report then compared to ED-2

$$\alpha_{rel} = 1.07$$

$$\mathcal{E} = 2.1 \quad \Delta t \text{ (const.)}$$

$$P = .78 \left(\frac{\pi}{4} (- \ln R)^2\right) \quad \text{(const.)}$$

This datum is suggestive of there being a tradeoff as the composition is changed from phosphate to fluorophosphate, that

$$\sigma = c n_2 .$$

If we further assume that the energy storage efficiency is relatively constant,

$$\alpha = k n_2 ,$$

then the extraction efficiency, total power per beam, and the peak power

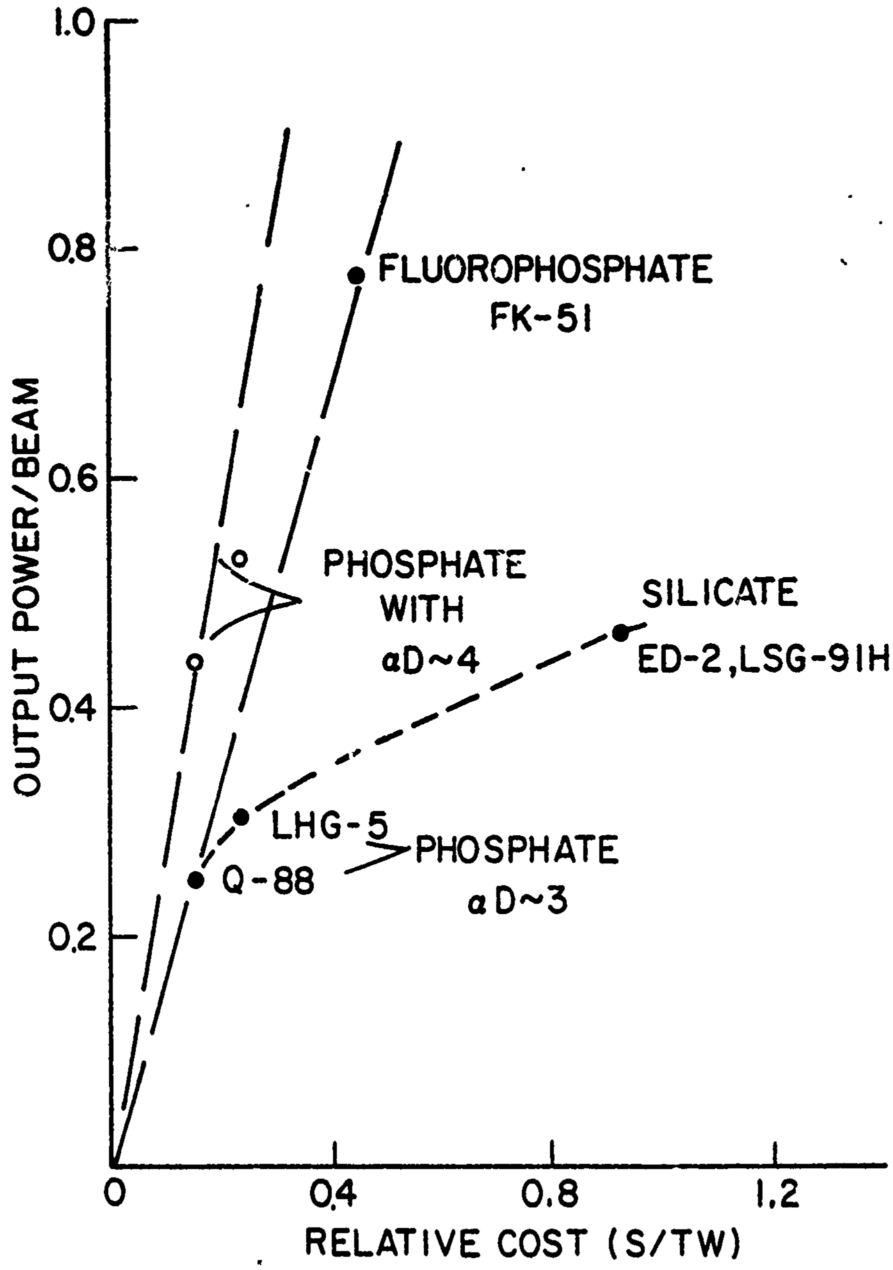

Fig. 2.1 — Comparison of various laser glasses: The cost/TW vs the power per beam (both in relative units). Silicate, phosphate and fluorophosphate are shown with a parasitic restriction of $\alpha D = 3.0$. Also shown are the expectation for the two phosphates if $\alpha D = 4.0$ can be attained.

density for glasses of such a family scale as

$$\mathcal{E} \propto n_2 ,$$

$$P_T \propto \frac{1}{n_2^2} ,$$

and

$$I_f = (\text{const.}) .$$

This conjecture poses an intriguing tradeoff; a reduction of n_2 by a factor of two doubles the cost of laser components, but reduces the number of beams by a factor of four for a given total power. Clearly the question of the cost of targeting beams will sway a conclusion as to which glass is superior.

2.3.2 <u>αD Restriction</u> - Implicit in the above comparison are several assumptions which should be examined; they can modify the cost vs number of beams tradeoff. We have assumed that in all cases we are considering Brewster angle disc amplifiers where the discs have an elliptical profile (nominally 2:1 ratio between major and minor axes) and that in all cases the parasitic limit on αD_M is the same. If we assume that the maximum value of $\alpha D = 3.0$ we can characterize the beam sizes for the maximum-power amplifier chain made of each glass. Silicate glass disc amplifiers have operated well at values of $\alpha = .085\ cm^{-1}$ and there are minimal damage problems. This would argue that the maximum beam diameter to stay beneath the parasitic limit for silicate glass would be:

$$D_s = 17.5 \text{ cm} .$$

Using the values of relative gains in Table 2.2 and the estimate for fluorophosphate glass FK-51, one can evolve the following set of beam-diameter limits (Table 2.3);

Table 2.3 - Beam-Diameter Limits

Glass	Beam Diameter (cm)
Old silicate	40
ED-2	17.5
LHG-5	9.75
Q-88	7.9
Fluorophosphate* FK-51	16.1 cm

The most interesting entries here are the phosphates and fluorophosphates. If a fluorophosphate with an $n_2 = 5 \times 10^{-14}$ could be made with acceptable and mechanical properties, σ might be in the range of $\sigma \simeq 1.5 \times 10^{-20}$ cm^2; the peak power per beam could go to

$$P_T = 2\left(\frac{\pi}{4}(-\ln R)^2\right) \quad (\text{const.}),$$

while the cost per terawatt would rise by a factor of 1.6. Relative to the good silicate glass this laser would produce 4.5 times the power per beam at 78% of the cost per terawatt of the silicate-glass system. That is to say, it appears that the major impact of very low n_2 fluorophosphates may be to increase the power per beam without significantly decreasing the cost per terawatt.

With a phosphate glass relative to the silicates the cost per terawatt could be radically decreased, but only at the expense of increasing the number of beams. For example, with Q-88 a decrease in the cost per terawatt of 5.7 appears possible, but only at the expense of an increase to twice the number of beams needed with silicate glass.

*Fluorophosphate with $n_2 = 8 \times 10^{-14}$. If a glass of this type can be made with $n_2 = 5 \times 10^{-14}$ then $D \approx 26$ cm.

It seems clear that there may be a very large premium on techniques which would allow very large numbers of beams to be focused with the precision required for laser-plasma experiments. The concept of arrays of laser beams formed into a smaller number of composite beams is not entirely new. The 216 beam system under construction at the Lebedev Institute in the USSR is designed along these lines.[15] Carmen at Los Alamos (LASL) has also considered some of the possible array schemes;[22] for very large glass-laser systems the economic advantages would seem to compel serious study of the engineering aspects and constraints on this approach.

Another question should be raised in connection with the issue of beam size and parasitic constraints, and that is the question of whether $\alpha D = 3$ is in fact an appropriate value for the phosphate and fluorophosphate laser glasses. For silicate glasses with a glass-edge coating the index of present claddings is roughly 1.1 times the index of the disc. This indeed corresponds to a threshold of $\alpha D \approx 3.0$.

For the phosphate glasses, however, a cladding has already been developed where the cladding index is only 1.015 times the index of the laser glass. Of itself this should allow operation at $\alpha D \geq 4.0$. The question is not one of parasitic oscillation, but one of fluorescence amplification and depumping of the laser disc. This effect will require greater amounts of absorbed energy per unit population inversion. However, the optical coupling of lamp light to discs will also increase as the amplifier diameter is scaled up using the same diameter flashlamps and the same mounting tolerance. Using Trenholme's analysis of fluorescent depumping[8] we would estimate that a scaled up version of the present NRL amplifier could achieve $\alpha D = 3.6 - 3.7$ with the Kigre Q-88 glass at $D = 10.5$ cm.* With the available edge coatings $(\alpha D)_{crit.} \simeq 5.5$ for parasitic oscillation, so it may be possible to increase the doping enough to reach $\alpha D = 4.0$ without provoking the face-parasitic mode. The benefit of doing this on the phosphate glass would be relatively large:

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*Without increasing the flashlamp loading.

the power per beam would increase by a factor of 1.77 while maintaining the same cost effectiveness. With this increase the total power per beam from phosphate glass would essentially equal the power per beam from silicate glass, but the cost per TW would be reduced by a factor of 5.7.

With low n_2 ($\sim 5 \times 10^{-14}$ esu) fluorophosphates while it might be possible to achieve similar (1.79 x) increases in output per beam, the improvement in flashlamp coupling with a 4:3 scale up of disc size from $\simeq$ 26 cm would be less, so the flashlamps would have to be pumped harder. Additionally, the lower index of refraction (< 1.50) would necessitate improved edge coatings or perhaps liquid edge coatings. This could further increase the output power per beam by as much as a factor of 7.5 over the silicate power per beam, but once again it would not improve the cost/TW which for this factor of power enhancement would equal 78% of the silicate cost/TW.

2.3.3 Long-pulse analysis - As discussed in Sec. 1.1 the long-pulse case we are interested in is long only by comparison to the earlier short-pulse case; we are talking of pulses only a few nanoseconds in duration, but long enough so that self-focusing does not limit the power density. The amplifiers in this case, however, will still be effectively a three-level amplifier, as the pulses are short compared to the estimated lower-level life-time of 10 ns.[23,24,25]

We can estimate the cost effectiveness of various glasses by using Eq. (2.15)

$$\mathcal{E} = \frac{\alpha(\text{const.})}{\left[\ln\left(e^{E_f/E_s} - 1\right) - \ln\left(e^{E_o/E_s} - 1\right)\right]} ,$$

where E_o and E_f are input- and output-energy densities and E_s, the saturation flux, is defined as $E_s = h\nu/2\sigma$.

There is no unique answer which will cover all cases, but we can best illustrate the differences from glass to glass by using several model amplifiers and several values of the allowable average output energy density. The actual energy density in the discs will be reduced

by a value of ~ 1.85 because of the Brewster angle, so we will denote these cases by the average energy density which would be incident on an optical component at normal incidence in the beam. Values used were 7.5 J/cm^2 (median expectation), 5 J/cm^2 and 10 J/cm^2. It should be noted that the peak on-axis energy density will be approximately twice these values.

The glasses considered here are not intended to be an all inclusive listing, but are representative of interesting glasses. Table 2.4 lists the parameters relevant for the long-pulse analysis.

Table 2.4 - Glass Properties

Glass	$E_s (J/cm^2)$	$n_2 \times 10^{13}$ esu	α(relative)
ED-2	3.22	1.4	1.0
Q-88	2.24	1.2	2.2
Fluorophosphate FK-51	3.75	0.8	1.08
Fluorophosphate A*	6.26	0.5	.65

2.3.3.1 Median expectation case - 7.5 J/cm^2 - Brewster angle incidence reduces this level to 4 J/cm^2 in the disc. Three amplifiers were considered:

- Amplifier A amplified the pulse 10 times from 0.4 J/cm^2 to 4 J/cm^2.
- Amplifier B amplified the pulse 100 times from 0.04 J/cm^2 to 4 J/cm^2.
- Amplifier C amplified the pulse by a factor of two from 2 J/cm^2 to 4 J/cm^2.

*Fluorophosphate A is a hypothetical "ultimate" fluorophosphate with $n_2 = 5 \times 10^{-14}$ esu and $\sigma = 1.5 \times 10^{-20}$ cm^2.

The results for the relative cost effectiveness of different amplifiers in this case are summarized in Table 2.5 normalized to Amplifier A with ED-2

Table 2.5 - Amplifier Efficiency - 7.5 J/cm^2 (4.0 J/cm^2 on disc)

Glass	Ampl. A	Ampl. B	Ampl. C
ED-2	1.00	.553	2.78
Q-88	1.99	1.15	5.2
Fluorophosphate FK-51	1.12	.611	3.19
Fluorophosphate A	.73	.386	2.2

2.3.3.2 High-damage threshold case - 10 J/cm^2 - Here the amplifier characteristics were the same, i.e., G = 10 (A); G = 100 (B); G = 2 (C). The same normalization was used as in Case 1. The results are given in Table 2.6.

Table 2.6 - Amplifier Efficiency - 10 J/cm^2 (5.4 J/cm^2 on disc)

Glass	Ampl. A	Ampl. B	Ampl. C
ED-2	.925	.53	2.44
Q-88	1.78	1.07	4.38
Fluorophosphate FK-51	1.04	.586	2.83
Fluorophosphate A	.700	.374	2.02

2.3.3.3 Low-damage threshold case - 5 J/cm^2

Table 2.7 - Amplifier Efficiency - 5 J/cm^2 (2.7 J/cm^2 on disc)

Glass	Ampl. A	Ampl. B	Ampl. C
ED-2	1.08	.58	3.26
Q-88	2.24	1.22	6.2
Fluorophosphate FK-51	1.19	.635	3.54
Fluorophosphate A	.76	.395	2.36

The three different amplifier designs represent choices of staging of laser amplifiers which might be implemented in practice:

- Amplifier A represents a design choice which is reasonable where the pulse duration is short enough that self-focusing is a minor but non-negligible constraint. The overall-system efficiency will be relatively high although the peak power will not be as high as with Amplifier B.

- Amplifier B represents a design choice which could be used when self-focusing is a problem. The peak power per unit self-focusing gain is highest for this choice, but the overall efficiency is not as high.

- Amplifier C is representative of amplifiers in a system designed for long enough pulses where self-focusing is negligible. It provides maximum-extraction efficiency while keeping the energy density below a limit. To use this option for short pulses, a large number of high-power-spatial filters would be necessary and the phase distortion would be greatest with this approach.

In all cases the Q-88 phosphate was more cost effective than ED-2 by a factor which ranged between 1.8 and 2.1. It was also more cost

effective than FK-51 fluorophosphate by a factor which ranged between 1.55 and 1.925 and more cost effective than fluorophosphate A by a factor between 2.15 and 3.09. Interestingly enough, the cost effectiveness of fluorophosphate A was less than ED-2 by 20 to 30% which was the inverse of the result in the short-pulse case.

2.4 Summary-Laser Materials

In the preceding section we compared the various laser glasses using models for short-pulse and long-pulse operation. Relative to a silicate glass, ED-2 or LSG-91H, the phosphates and fluorophosphates have interesting properties and on balance are quite superior to the silicates.

2.4.1 Phosphate glass Q-88 - This glass showed the largest potential for cost reduction; a factor of 5.7 for short-pulse operation and a factor of two for long pulses relative to ED-2. These were caused by the large induced emission cross section and excellent absorption efficiency. The resultant large net gains, however, cause another problem - the parasitic limit on beam diameter will be reached at relatively small-beam diameters. There appears to be a good chance to ease this restriction somewhat, as this glass appears to be well suited to building an amplifier with $\alpha D \simeq 4$ rather than $\alpha D \leq 3$, but utilization of this glass for very large systems will still require development of a methodology for handling and combining large numbers of beams.

2.4.2 Fluorophosphate FK-51 - A glass with intermediate values of n_2 (8×10^{-14} esu) and induced emission cross section ($\sigma \sim 2.5 \times 10^{-20}$ cm^2). For short-pulse operation this glass showed a potential for a factor of two cost reduction over silicate glass. In the long-pulse case this was reduced to about a 10 - 15% advantage. The beam size restrictions with this glass are essentially the same as with ED-2. This glass would be the best choice for a retrofit on large aperture systems designed for use with ED-2 or LSG-91H; it would result in an increase of a factor of 1.75 in output power. For very large systems the number of beams would still be large.

2.4.3 <u>Fluorophosphate A</u> - A (hypothetical) glass with a low n_2 (5×10^{-14} esu) and a correspondingly small induced emission cross section ($\sigma = 1.5 \times 10^{-20}$ cm^2). In the short-pulse limit the cost per-unit output was about 80% of the value for ED-2 while for long pulses it actually appears it would be 20 - 25% more costly. It would, however, allow the largest beams to be constructed consistent with parasitic limits. There would be little or no cost savings with this glass.

Overall, the phosphates such as Q-88 show a high enough potential for substantial cost savings that the problem of handling and combining the large number of beams is worthy of consideration.

3. USE OF PHOSPHATE-FLUOROPHOSPHATE GLASSES TO UPGRADE EXISTING SYSTEMS

In this section we will examine the impact of phosphate and fluorophosphate glasses on two existing systems; Argus at LLL and Pharos II at NRL. These two systems span the range of silicate systems from large aperture (Argus at 20 cm) to small systems (Pharos II at 6.7 cm). Argus essentially represents 2 beams of the twenty beams of the Shiva system, so the performance levels should scale to Shiva; Pharos II represents a system small enough in diameter that it should not be parasitic limited even with the highest gain glass available (with Q-88, $\alpha D = 2.6$). The impact of these glasses on other intermediate size systems can be inferred from these results.

3.1 Silicate-Glass Results - Argus vs Pharos II

Each beam of Argus is staged up to 20 cm aperture final amplifiers. The beam is spatially filtered four times through the system to reduce small-scale self-focusing growth. The gain coefficient of the final amplifiers is 6%/cm and good beams have been obtained at up to 1.2 TW/beam.[26,27,*]

Each beam of the Pharos II laser system is staged up to 6.7 cm aperture final stage amplifiers. The beam is spatially filtered once before the entrance to the high-power amplifiers. The gain coefficient of the final amplifiers is 8%/cm and good beams have been obtained up to 0.36 TW/beam.

The staging of the two systems is similar, and based on small-scale self-focusing theory it would be expected that the output intensities would be proportional to αx (area) if the same spatial-noise spectrum were present. The reported outputs are not in the ratio 6.7 to one but rather in the ratio of 3.3 to one, but this appears to be due to the poor present filling factor on Argus.

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*At present the beam does not adequately fill the final amplifiers, $D_{beam} \simeq 0.7\ D_{amp}$. It is expected that with improved filling the power per beam will increase to 2.0 TW.

There are several results which suggest that the spatial-noise spectrum in Pharos II is of much smaller amplitude than in the Livermore system, and much more spatial filtering has been required in Argus to reach comparable outputs.

(a) Comparable spatial filtering tests were performed sometime ago. These constitute a test of the spatial-noise spectrum. On Pharos II the spatial filter had 100% transmission up to a value of the small-scale growth factor $B = 7.5$ and had 80% transmission at $B = 10.5$.[28]* The Cyclops system at LLL (a system similar to Argus but with one beam and less spatial filtering) would depart from 100% transmission above $B = 2.5$ and was down to 80% transmission at $B = 4$.[29]

(b) Early tests at NRL before the Faraday rotator isolator systems were installed showed that indeed I_o was proportional to α and also at that point the breakup value was equal to $B = 10.8$,[6] suggesting that introduction of the Faraday rotators and polarizers enhanced the spatial-noise spectrum. It is possible that the large comparative number of components in Argus result in a greater noise spectrum.

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*The so-called B integral is a measure of the peak-phase retardation in radians. It is defined as

$$B(Z) = \frac{8\pi^2}{\lambda n_o c} \int_0^Z n_2 I dZ; \quad B(Z) = 2.4 \text{ at} \int_0^Z I dZ = 10^{11} \text{ W/cm}$$

with silicate glass.

(c) The oscillator-preamplifier section of Pharos II is very clean spatially. In experiments on pulse compression this pulse was diverted from the main beam and sent through cells of CS_2, a very high n_2 material, to obtain a large frequency chirp. Total B integral values in excess of B = 30 could be obtained before small-scale self-focusing became evident.[30]

The overall observation would be that indeed the results are different and that the LLL laser must have a higher amplitude spatial noise spectrum. This may be due to the larger number of components. It may also be due to the larger aperture of the laser, as diffraction of high-frequency ripples out of the beam will be less effective. It would be expected that with multiple-spatial filtering these additional handicaps for the large system at LLL could be overcome, and this may be the case.

Pending achievement of final silicate glass performance levels on Argus we will not intercompare between Pharos II and Argus, but will discuss the effects of introduction of the various glasses on each system in terms improvement of the present level of performance.

3.2 Pharos II

A schematic of Pharos II is shown in Fig. 3.1. Amplifiers ∅23, ∅32 and ∅45 are CGE rod amplifiers used with $ZnC\ell_2$ index matching liquid to increase the gain by suppressing parasitic oscillation.[31] The amplifiers labeled ∅67 are disc amplifier modules normally operating with a gain coefficient of 8%/cm. With ED-2 silicate glass the output per beam has been tested up to 36 J in a 100 ps pulse without beam breakup. At this level the total B integral has a value of 7.5; 2/3 of this in the disc amplifiers and 1/3 in the rod amplifiers.

These amplifiers are relatively well suited to operation with the high gain phosphate glasses since the amplifier diameter is below the αD = 3.0 limit. In recents tests with the Kigre Q-88 phosphate glasses very large gain coefficients have been obtained relative to the silicate glasses at the normal pump level. At line-center gains of 18.5%/cm were obtained.[21] This represents a value of αD = 2.6. With the well

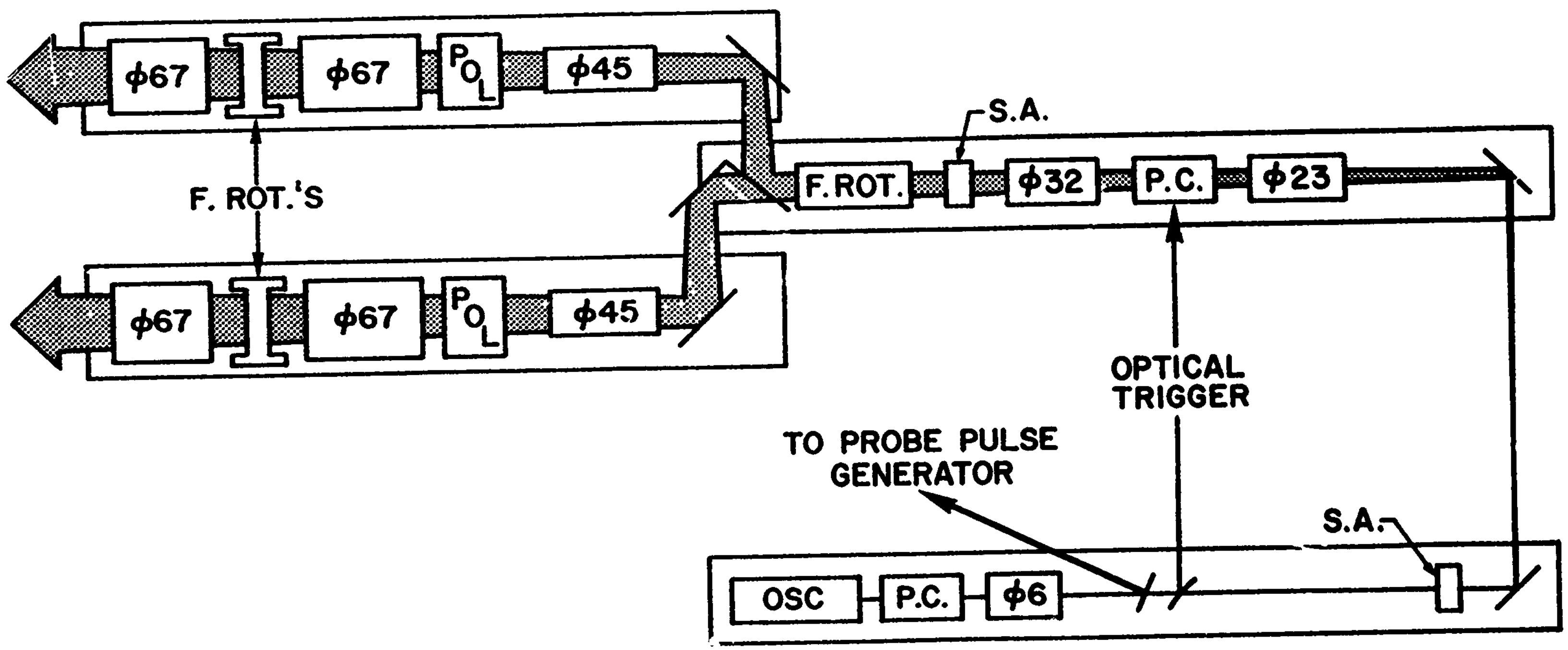

Fig. 3.1 — Pharos II schematic. The oscillator preamplifier section generates a pulse of nominal energy 15 mJ in 100 ps. This is amplified to 0.5 J in the intermediate amplifier section and then split into two beams. The final amplification stages consist of a 45 mm diameter rod amplifier ($e^{\alpha\ell} \simeq 30$) and two 67 mm aperture disc amplifiers ($e^{\alpha\ell} \simeq 10$).

matched edge coating on this glass it appears that with further slight optimization a gain of 20%/cm may be practical.

Even with the gain attained to date a substantial short-pulse performance improvement should result from replacing the silicate glass with phosphate glass. The relative value of α/n_2 will increase by a factor of 2.6 so one would expect that the output level could increase to 0.9 TW. In fact it will increase to a greater degree than this factor alone because the increased gain of the disk modules ($e^{\alpha\ell} \geq 120$ vs $e^{\alpha\ell} \simeq 10$) will allow the rod system operating levels to be reduced substantially (and α/n_2 will also increase for the rods by a factor of $\sim$ 1.6). For the same total B integral = 7.5, the short-pulse output can be increased to 1.2 TW at the gain level (17.5%/cm) measured at our routine operating level and 1.5 TW if the gain is increased to 20%/cm.

This is a large enough increase in peak power that the assumption of no saturation becomes invalid for pulses much longer than 50 ps. A more sophisticated computation is relatively straightforward to do in a case where the ratio of active gain to passive loss is very high and the amplifier is not too heavily saturated ($E < 3\ E_s$). Franz and Nodvik first derived an equation for the instantaneous intensity in a lossless amplifier which we can use, rather than the small-signal gain approximation.[13]

$$I(Z,\ t) = \frac{I_o(t - Z/c)}{1 - \left\{1 - \exp - \left[\sigma \int_o^Z N_o(Z)dZ\right]\right\} \exp\left[-\int_{-\infty}^{t-Z/c} \frac{I_o(t')}{E_s}\, dt'\right]} . \tag{3.1}$$

We can simplify this equation if we assume the inversion is constant along the amplifier $\sigma n_o(Z) = \sigma n_o = \alpha$ and we can note that in the present case the second-exponential term is just the integrated energy

density from the start of the input pulse to the peak. Equation (3.1) then becomes

$$I(Z, t) = \frac{I_o(t - Z/c)}{1 - \left\{1 - \exp(-\alpha Z)\right\} \exp\left(\frac{-E_o(t - Z/c)}{E_s}\right)} . \qquad (3.2)$$

If we denote the exponential energy term by $\beta(t - Z/c)$ and insert this formula in the B integral formula we obtain an integration

$$B(Z, t) = \frac{8\pi^2}{n_o\lambda c} n_2 \frac{I_o(t - Z/c)}{\alpha} \left[\frac{\alpha Z + \ell n\,(1 - \beta + \beta e^{-\alpha Z})}{1 - \beta}\right] \qquad (3.3)$$

as compared to the small-signal gain result

$$B(Z, t) = \frac{8\pi^2}{n_o\lambda c} n_2 \frac{I_o(t - Z/c)}{\alpha} \left[e^{\alpha Z} - 1\right] . \qquad (3.4)$$

For our systems calculations we will make two assumptions to simplify the calculation:

- The peak point of the input pulse transforms into the peak of the output pulse.
- The input pulse is symmetric in time, that is if we take $I_o(t - Z/c)$ to be the peak of the input pulse, $\mathcal{E}_o(t - Z/c)$ equals half of the total input energy density.

These assumptions are not generally correct as it can be verified from Eq. (3.2) that as the input energy is increased the peak of the amplified pulse will shift forward onto the leading edge of the input pulse, and the appropriate input energy density will be less than half of the total density of the input pulse, but for the case we will consider, i.e. 100 ps pulses, these assumptions are very nearly correct. Additionally

errors introduced by use of these assumptions will overestimate the B integral and lead to a conservative estimate of the output power.

Under the same assumptions on total B integral as before we find that at 17.5%/cm the 100 ps output will be 1.04 TW/beam and at a gain of 20%/cm the output will be 1.15 TW/beam. The detailed B integral budgets are given below in Table 3.1.

Several points are immediately clear from Table 3.1. Despite saturation effects the output will still increase by an amount that is approximately α/n_2 for the disc amplifiers because the staging has been improved for maximum power output. While increasing the output power

Table 3.1 - 100 ps output at $B_T = 7.6$

Component	Silicate B values	Phosphate (.175 cm^{-1}) B values	Phosphate (.2 cm^{-1}) B values
Rod system	2.090	.32	.22
Lens + polarizer	.175	.04	.02
Disc No. 1	.965	.54	.42
Faraday rotator	.464	.43	.33
Disc No. 2	3.180	4.40	4.47
Output window	.750	1.79	2.09
B_{TOTAL}	7.62	7.52	7.55
E(J)/beam	37.5	104 J	115 J

substantially it has also been possible to lower the input power substantially. There are also clear advantages to be gained by replacing the final disc amplifier output window with a thinner window as in these examples the B integral of the window is 25 - 28% of the total. It would appear reasonable to expect that the output could be increased by ~ 10%

without heroic measures. The window calculation also suggests that to avoid excessive self-focusing growth in the targeting optics it also appears that the beam should be diverged through the disc amplifiers to give a larger beam diameter in the target room.

It also appears possible to simplify the driver system because the B integral is so low in this part of the system and because the drive-pulse requirements decrease so strikingly; the rod output in the 17.5%/cm case was only one joule and was half that in the 20%/cm case. It appears that both 45 mm amplifiers could be removed in the higher gain case. This would improve the overall efficiency of the laser.

With these changes the overall efficiency at 100 ps would improve from 0.018% to approximately 0.07%, a net factor of four.

For longer pulses the major system limitation would be damage either to the final laser discs or to downstream components. Energies up to 250 J/beam could be generated for pulses 300 ps in duration or longer with no anticipated laser damage problems. In fact the prediction is that this system could attain 500 J/beam in a few nanoseconds. The beam bending and focusing optics would be the limitation in this case. It appears that for long ($\sim$ 1 ns) pulses the overall efficiency would be greater than or equal to 0.14%. This is approximately one and a half times the efficiency with silicate glass and the present staging ($\sim$ .095%).

The question of damage to the beam-bending optics is far from trivial. In the tests reported by Leppelmeier beam turning mirrors were identified as having significantly lower damage thresholds than anti-reflection coatings or polarizers.[32] The Shiva projections seem to be keyed to these measurements.[33] These measurements are, however, not the only ones reported in the literature. Newman has reported damage thresholds for reflective coatings which in some cases are higher than the LLL measurements by a factor of 1.8.[34] In either case, the use of phosphate glass in the NRL system will result in the solution to the self-focusing problem to the extent that mirror damage appears probable unless the beam is expanded to a larger area between the laser output and the turning mirrors on the target chamber. Figure 3.2 shows the expected

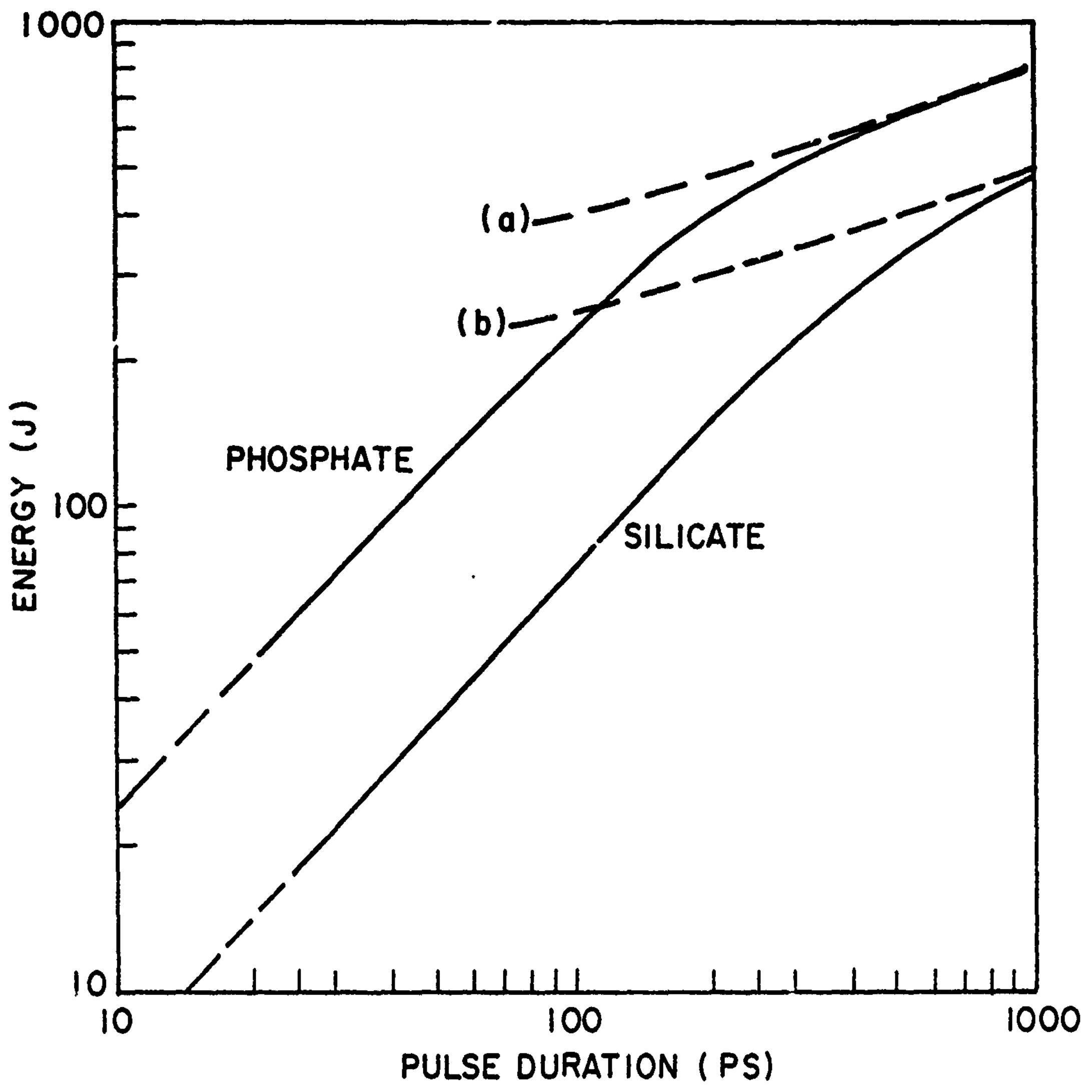

Fig. 3.2 — Performance of the Pharos II system for phosphate and silicate glass. Mirror damage limits (a) and (b) correspond to levels measured by LASL and LLL as discussed in the text.

laser performance vs pulse length with the assumption that the output beams are expanded to twice the beam area before reaching the turning mirrors. Also shown are the expected limits if either the LLL or LASL experiments prove to represent the best available coatings. If the LASL measurements are correct there may be no compromise of capability between 100 ps and several nanoseconds. If on the otherhand the LLL experiments represent reality, the operation for pulses shorter than 100 ps may be unaffected but between 100 ps and a nanosecond the performance may be mirror limited by as much as a factor of 1.6.

It should be noted that the identical limits apply to other lasers using phosphate or fluorophosphate laser glass since they will be capable of the same intensity. The major problem with successfully exploiting the new and improved laser materials is going to be damage to dielectric coatings. A systematic effort to improve the levels at which coatings can operate will be necessary to allow us to benefit from "solving" the self-focusing problems.

Given the unresolved state of coating technology and the unknown level that improved coatings will be capable of attaining in the near future, in latter sections of this report we will give all beam size estimates in terms of the laser. The reader must bear in mind that if substantial progress is not made in coatings the focusing optics may have to have a substantially larger diameter than the laser aperture.

In summary, with the NRL system installation of phosphate glass would improve the long pulse overall efficiency by about a factor of two; for 100 ps pulses the overall efficiency would improve by a factor of 4; for very short pulses ($\leq$ 50 ps), the factor would be approximately five.

The improvement factors are smaller than those given by the model because in the short-pulse case the staging with a phosphate glass substitution is essentially that for maximum peak power/beam rather than maximum overall efficiency. The difference in overall efficiency between these cases has been previously estimated in Sec. 2, and is of the order of the difference here.

For long pulses damage constraints on targeting optics inhibit the phosphate performance more than the silicate performance. In any

case the use of the phosphate glass in the NRL system markedly improves the laser performances for pulses less than 1 ns in duration.

3.3 Argus

The Argus system at LLL is a two-beam glass-laser system where the final beam diameter is approximately 20 cm in diameter. To date outputs in excess of a terawatt per beam have been produced in the course of bringing this system on line and ultimately it is expected to produce ~ 2 TW/beam with silicate glass.*

The impact of a phosphate glass such as Kigre Q-88 on Argus is relatively easy to assess. Since the amplifier diameter is well above the parasitic limit for Q-88 the gain coefficient cannot increase; rather the pump energy required to reach the gain coefficient will be reduced by $\sim 50 - 60\%$. The output in the short-pulse case can only increase by the ratio of n_2 values. The performance increase will be slight ($\sim 17\%$) but the overall efficiency will increase by a factor of 2.3 - 2.9. For long pulses the gain constraint combined with the lower saturation flux will tend to actually decrease the output although the pumping energy will decrease more rapidly.

The optimum choice of glass for an Argus retrofit is a fluorophosphate glass, such as the glass whose properties were reported by LLL scientists to be $\sigma \sim 2.5 \times 10^{-20}$ cm^2 and $n_2 = 8 \times 10^{-14}$ esu.[14] With a glass of this type the pumping energy would remain about the same, but the output could be expected to increase by a factor of $(1.4 \times .8) = 1.75$. The long-pulse performance would be basically unaffected. Argus predictions are shown in Fig. 3.3. The data are normalized to present performance. If the anticipated improvements in short-pulse performance occur all the curves will shift up in the short-pulse regime by a like factor. The long-pulse limit for Argus is expected to be ~ 1500 J/beam. With silicate glass and the present self-focusing limit it appears that

*In this initial iteration the filling factor for the final stage amplifiers was quite nonoptimal. This is expected to be remedied in the near future.

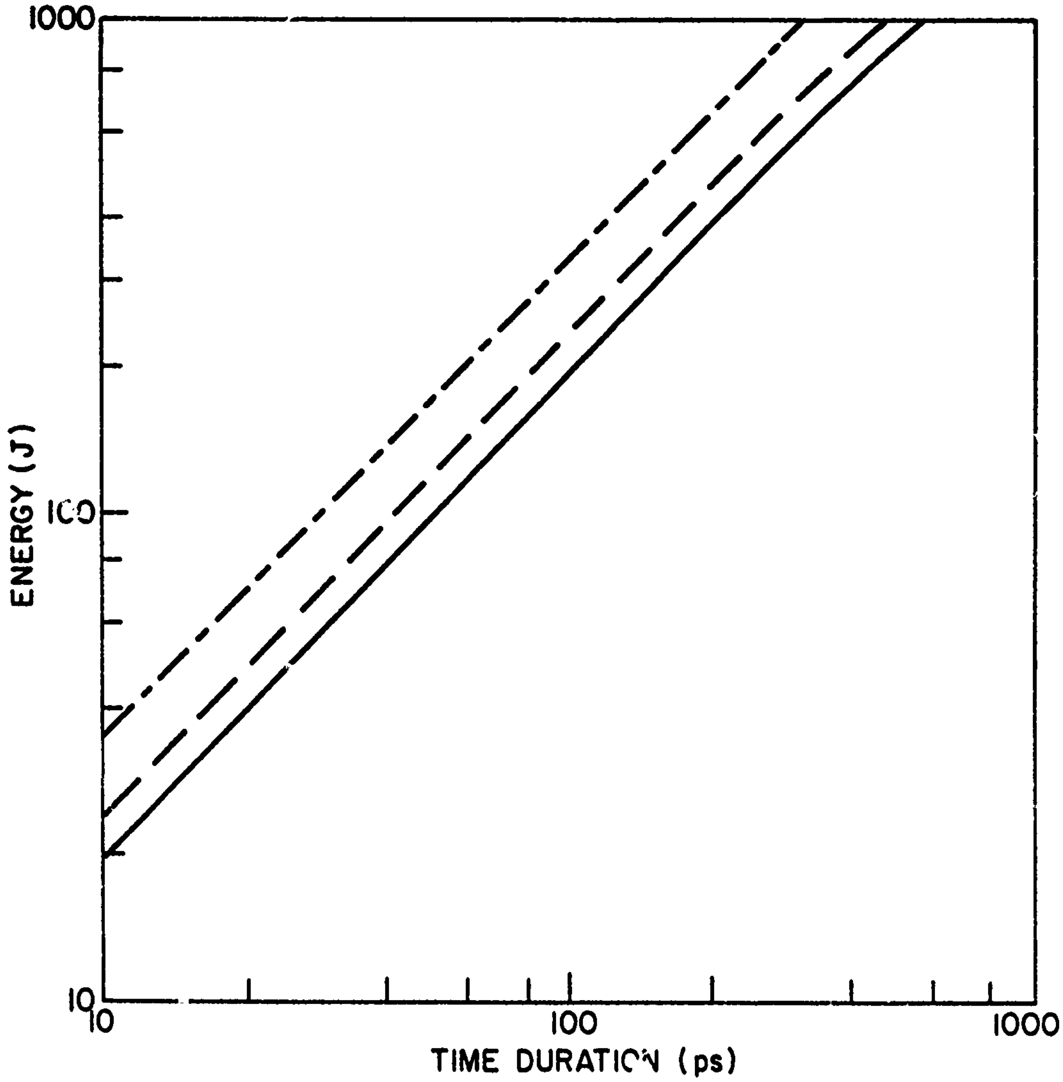

Fig. 3.3 — Argus performance for silicate, phosphate and fluorophosphate (FK-51) glass normalized to reported levels of 1.0 TW/beam. Silicate (——); phosphate (- - -); fluorophosphate (— - —).

this level cannot be reached for pulses shorter than 2 - 2.5 ns. With the fluorophosphate it would appear that this level could be achieved for 1.1 - 1.4 ns pulses.

3.4 Summary: Phosphate-Retrofitted Systems

The appropriate choice of phosphate or fluorophosphate in the NRL or LLL laser systems would substantially improve the performance levels for shorter pulses. For pulses longer than two nanoseconds the benefit would be much less striking because of damage limitations to downstream optical components. For the NRL system the impact of phosphate glass would be that output levels could be achieved at 250 ps which formerly could only be achieved at durations of a nanosecond (or slightly longer). For the Argus system at LLL the expected result would be to approximately double the short-pulse output if a fluorophosphate with approximately the same cross section as the silicate glass were used with a nonlinear index of refraction about half of the value for the silicate glass.

The performance predictions also appear consistent with the simple model developed in Sec. 2 which predicts that short pulse efficiency will vary as $\alpha^2(n_0/n_2)$. For long pulses it is clear that higher performance levels will be more readily attained but unanswered damage questions obscure the degree of advantage.

Thus, there is a substantial performance and economic advantage for high-gain systems of relatively small diameter. As noted earlier, however, this approach inevitably leads to a larger number of beams than pursuing a line of investigation concentrating on materials with low gain and a small nonlinear index of refraction.

4. SCALE UP OF THE NRL SYSTEM WITH PHOSPHATE-LASER GLASS

In the preceding section we saw that with high-gain phosphate glasses such as the Kigre Q-88 laser glass it appears reasonable to expect that the NRL laser system will generate greater than 1 TW/beam at 100 ps which represents a comparable output to that attained to date with the much larger and more expensive Argus system at LLL.

In this section we will first look at the economics of scaling up the NRL system to the projected Shiva level and then look at the economics of a larger system on the 100 - 200 TW level. In considering the phosphate alternative to Shiva, we will first consider just building N copies of the NRL system and then look at two mutually nonexclusive ways to boost the power per beam: larger amplifiers and composite apertures.

4.1 Shiva System

Shiva as presently conceived is to be build as ten of the Argus systems. It is hoped that the power per beam will be 1.0 - 1.5 TW at 100 ps TW/beam on each of the total of twenty beams (20 - 30 TW total) with a total-energy output in excess of 1.2×10^4 J in a nanosecond pulse.

4.1.1 Copy of present NRL system - Sixteen copies of the NRL Pharos II system would provide 32 beams on target, 36 TW short pulse and 8×10^3 J in a nanosecond pulse. Twenty copies would provide 40 beams on target, 45 TW and 10^4 J in a nanosecond. We will compute both choices as one matches the peak power and the other matches the long-pulse performance.

Shiva

No. of Beams - 20
Energy Stored - 30 MJ
Glass Volume - 0.5 m^3

Peak Power - 100 ps = 20 - 30 TW
Efficiency - .007 - .01%

Energy Out - 1 ns = 12 kJ
Efficiency - .04%

16 x (Pharos II) — No. of Beams - 32

Energy Stored - 5.6 MJ

Glass Volume - 0.09 m^3

Peak Power - 100 ps = 37 TW

Efficiency - .066%

Energy Out - 1 ns = 8 kJ

Efficiency - 0.14%

20 x (Pharos II) — No. of Beams - 40

Energy Stored - 7 MJ

Glass Volume - 0.11 m^3

Peak Power - 100 ps = 46 TW

Efficiency - .066%

Energy Out - 1 ns = 10 kJ

Efficiency - 0.14%

One other comparison may be relevant to a costing comparison. SHIVA will use $\sim 0.5\ m^3$ of laser glass while the 16 x (Pharos II) would use 0.09 m^3 of glass and the 20 x (Pharos II) would use 0.11 m^3. It would seem reasonable to expect that this approach would result in a cost-reduction factor of 4 to 5 for the laser.

4.1.2 Methods of reducing the number of beams - Two techniques appear possible candidates for reducing the number of beams on the Shiva-alternate system.

4.1.2.1 Larger final stage - As was discussed earlier (Sec. 2.3.2) with the phosphate glasses there appears to be a reasonable chance of building larger amplifiers with $\alpha D_M \sim 3.7$ at D = 10.5 cm. The final-disc module on each chain could be replaced by such a module and the expectations would be an increase in short-pulse (100 ps) output to 2.5 TW/beam and nanosecond output to 600 J/beam. Six Pharos II-like systems would then

meet the peak-power specification and eight would essentially meet the nanosecond specification. Systems parameters for these choices would be:

<u>6 x Pharos II'</u>	No. of Beams - 12
(D = 10.5 cm)	Energy Stored - 3.0 MJ
	Glass Volume - 0.043 m^3
	Peak Power - 100 ps = 30 TW
	Efficiency - 0.1%
	Energy Out - 1 ns = 7.2 kJ
	Efficiency - 0.24%
<u>8 x Pharos II'</u>	No. of Beams - 16
(D = 10.5 cm)	Energy Stored = 4.0 MJ
	Glass Volume - .057 m^3
	Peak Power - 100 ps = 40 TW
	Efficiency - 0.1%
	Energy Out - 1 ns = 9.6 kJ
	Efficiency - 0.24%

In this case, not only has the number of beams decreased, but additionally the efficiency has dramatically increased. In large part the increase is a result of improved staging which will increase the overall efficiency. In Sec. 3.2 when the Pharos II retrofit was discussed it was noted that in neither case did this represent an optimum-efficiency retrofit, because the staging with phosphate would entail very inefficient operation of all amplifiers but the last disc amplifier. With the larger disc amplifier on the end of the chain, however, we can improve the energy extraction from the earlier part of the system by a factor of 2 or more. In the short-pulse case this will increase the B integral by 1.33 up to the second disc. Two approaches are possible to make up for this increment-in practice both would be implemented:

- As discussed before in Sec. 3.2, decrease the output window thickness to reduce its contribution to the B integral.
- Make the beam expander between the Faraday rotator and second-disc amplifier also function as a spatial filter.

In summation, this option is highly attractive. By reoptimizing the staging we have almost doubled the efficiency and have also reduced the number of beams to a level below that in Shiva. The amount of laser glass is further reduced to .035 m^3 (12 beam) and .045 m^3 (16 beam). For short pulses it appears that the cost reduction relative to Shiva could be almost an order of magnitude. This is in excess of our scaling-law prediction (p. 16) of a factor of 6.2. The reasons for this discrepancy are related to several factors in the Shiva design which are non-optimal from an efficiency standpoint:

(a) The final amplifiers are too large. The disc diameter is above the parasitic limit for silicate glass at 8%/cm. This lowers the overall efficiency of these major components.

(b) The staging is not optimal from an overall efficiency standpoint but rather favors power per beam at the expense of efficiency.

4.1.2.2 Beam combination - In the preceding sections we have seen that the maximum intensity per beam would be 1.0 - 2.5 TW/beam. For net yield experiments peak powers in the range of 100 - 200 TW on target may be required. This would lead to estimates of 40 (optimistic) to 200 (pessimistic) beams which must be aligned on the target. This is not necessarily bad from a physical standpoint as one would expect the illumination uniformity to improve. From a practical standpoint the alignment problem is obviously nontrivial and the turn-around time for changing the focusing system as targets are changed increases. Some premium would be expected if we could reduce the number of beams which must be aligned by grouping laser beams together. Several techniques to achieve this end have been tried at several laboratories. These include:

(a) Polarizer-Beam Combination - The types of lasers under consideration here produce linearly-polarized beams. KMS has used a dielectric polarizer to combine two linearly-polarized beams into a circularly-polarized beam. This technique does not appear too attractive because the reduction in the number of focused beams is only a factor of two. More importantly, with phosphate glass the single-beam-performance levels will already be limited by damage and the combined beam would be more likely to cause damage.

(b) Amplifier Arrays - At the Lebedev Institute in the USSR a 216 beam-laser system is under construction. The final amplifiers in this system are arranged in groups of nine per beam and then 2 groups of nine of orthogonal polarization are combined with a prism. The result is that the 216 beams are reduced to 12 beams which have to be targeted.

It is worth considering the properties of various simple arrays The simplest arrays are rectangular (2 x 2 and 3 x 3) and circular (seven nested beams). Table 4.1 gives the relevant properties of various arrays and Fig. 4.1 shows these symmetric close packed arrays.

Table 4.1 - Simple Arrays

Pattern	No. of Beams	Circular Diameter	Filling Factor
Rectangular 2 x 2	4	2.414 D	0.69
Rectangular 3 x 3	9	3.828 D	0.61
Circular	7	3 D	0.78

In considering how arrays of NRL style disc amplifiers will perform we will constrain ourselves to having all identical disc modules for

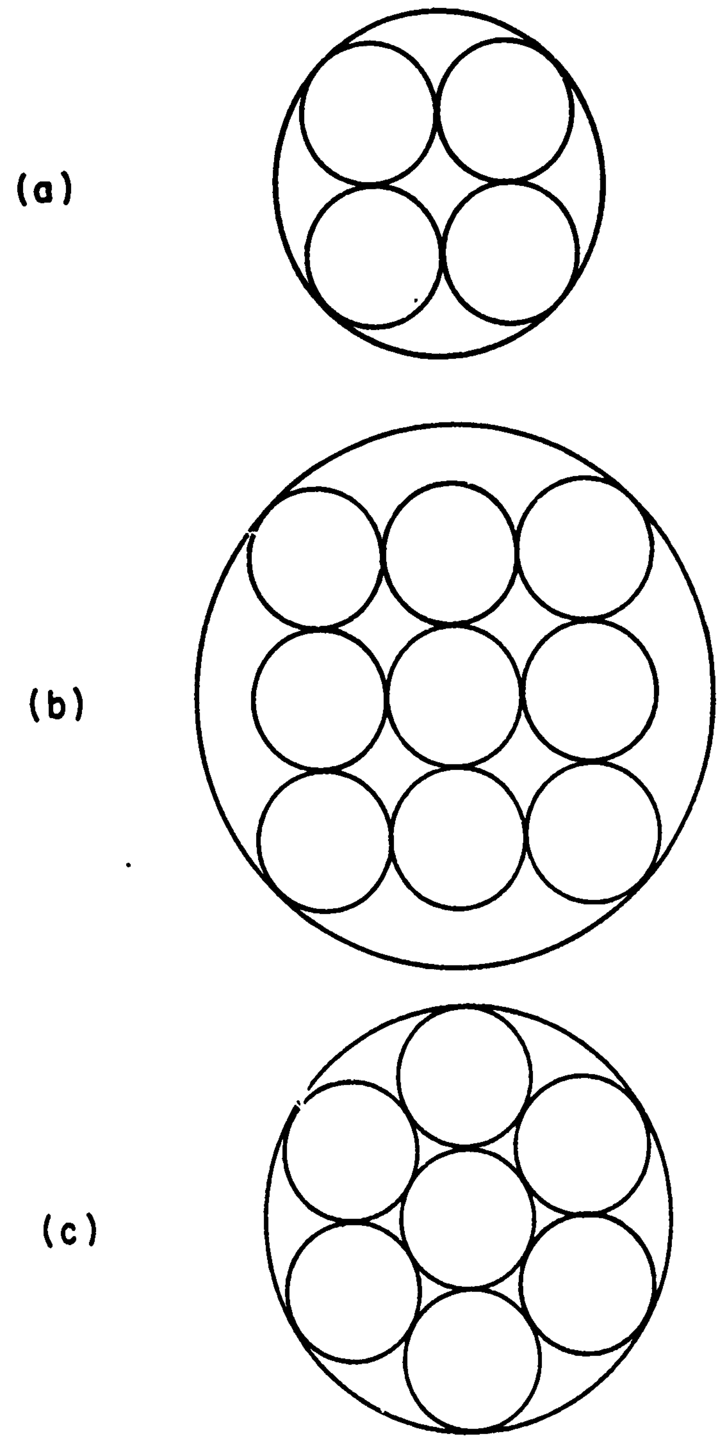

Fig. 4.1 — Three simple arrays. (a) four-way split approximates best multinanosecond choice for the amplifiers modeled. (b) nine-way split would be choice for $\Delta\tau < 50$ ps and (c) seven-fold split which was best for 100-200 ps pulses.

the sake of simplicity. If we further constrain our design such that the output of the module driving the array is no higher than the output of each module in the array, we constrain the number of beams per array to be no more than the gain coefficient.

The gain varies with the pulse width because of saturation. For pulses shorter than 50 ps the gain is essentially the small signal gain, $G_o = 11.6$. For 100 ps pulses $G \simeq 7.5$ and at a nanosecond $G \approx 4.2$. The natural choices with these disc laser modules would then be seven-fold arrays at 100 ps and four-fold arrays at a nanosecond.

In actually building a system, other choices are possible, i.e. more discs per module in the array to increase G to a desired value for a particular pulse width. The major point, however, is that saturation will not allow an across the board optimization.

Figure 4.2 shows a schematic of a short-pulse (100 ps) system design using seven-beam arrays and the present 68 mm aperture-disc amplifiers. In the estimates it is assumed that each beam in the array has a Faraday rotator associated with it, and that there are two spatial filters in each beam path with a total-B integral ≈ 13. This approach would result in a short-pulse output of 32 TW, similar to the Shiva system and the system considered in Sec. 4.1.2.1 with a 10 cm amplifier but the output would consist of four composite beams, each of which would be compatible with 20 cm diameter focusing optics. The whole system could be driven by the present Pharos-II system (through the rod amplifiers).

<u>4 - 7 Beam Arrays</u>	No. of Beams - 4
(6.8 cm Amplifiers)	Diameter - 20 cm
	Energy Stored - 3 MJ
	Glass Volume - 0.032 m^3
	Peak Power - 100 ps = 32 TW
	Efficiency - 0.11%
	Energy Out - 1 ns = 5 kJ
	Efficiency - .17%

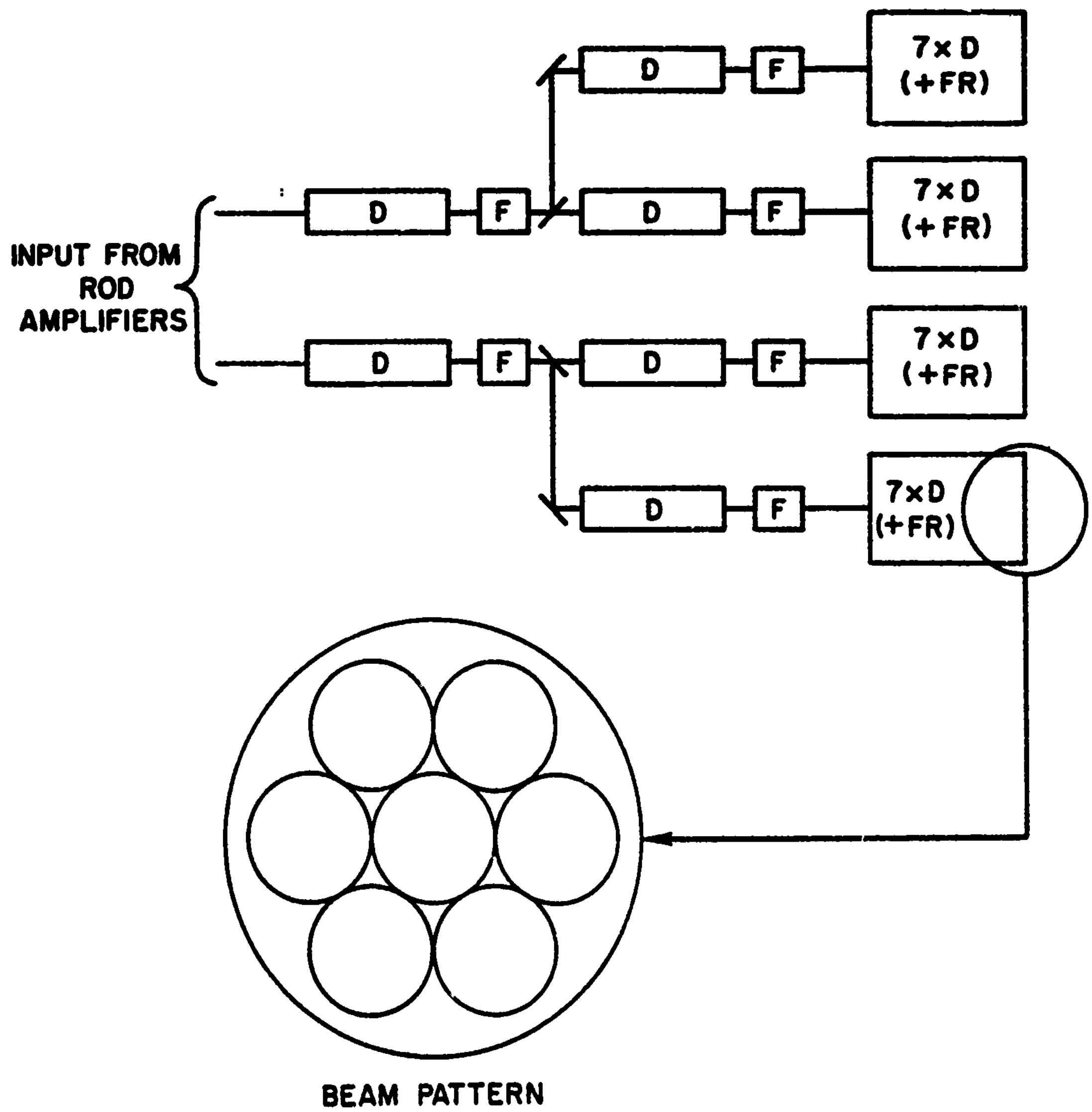

Fig. 4.2 — Array system equivalent for short pulses to the Shiva silicate glass design. Each of the four targetable beams consists of seven arrayed 6.8 cm amplifiers (with associated isolators).

If the 10.5 cm amplifiers discussed in Sec. 4.1.2.1 were used rather than the 6.8 cm amplifiers the array-beam size would increase to 30 cm and the output energy would increase by a factor of ~ 2.4 at the same efficiency. That is the laser would have the properties:

<u>4 - 7 Beam Arrays</u>	No. of Beams - 4
(10.5 cm amplifiers)	Diameter - 30 cm
	Energy Stored - 7.5 MJ
	Glass Volume - 0.077 m^3
	Peak Power - 100 ps = 77 TW
	Efficiency - 0.1%
	Energy Out - 1 ns = 12 kJ
	Efficiency - .17%

The chief advantage of the larger disc amplifiers would be a higher power, 19 TW per array vs 8 TW per array for the smaller amplifiers. The degree of complexity and efficiency would be the same in either case.

To modify these systems to operate well at a nanosecond two additional discs could be added per module. This would increase the nanosecond outputs to 7 and 17 kJ at an overall efficiency of 0.2%.

With either of the array systems it is likely that it would be possible to reduce the capacitor-bank size by grouping the laser amplifiers in a common-pumping cavity, such as is schematically shown in Fig. 4.3. This might increase the overall efficiency by as much as a third but would not increase any other cost elements and might increase the possibility of a very expensive catastrophe in the event of flashlamp failure.

In summary, with either larger amplifiers or arrays, or both it appears possible to exploit the high-overall efficiency of phosphate glass (~ 0.1% at 100 ps) and simultaneously decrease the number of beams which have to be independently aligned on target to a number comparable to or possibly smaller than that achievable with silicate glass.

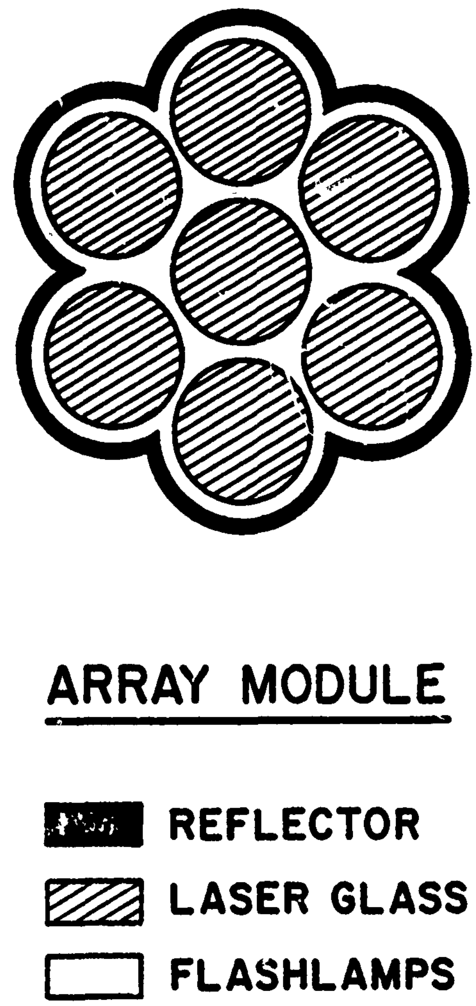

Fig. 4.3 — Seven beam disc module. By use of the common pumping cavity, the efficiency could be increased over seven discrete modules by 30-40%.

4.2 A 100 kJ System

The most attractive phosphate systems we have yet identified are the 7 and 10 cm array systems in that they have minimum beam count and maximum peak power and efficiency. Each package is essentially a four-beam device so larger numbers of beams could be constructed such as 12, 20 or 32 beams by copying either device 3, 5 or 8 times. The Shiva device at LLL will have a total-bank energy of 30 MJ and a total-laser-glass volume of $\sim 0.5\ m^3$. If we assume the system cost will scale as glass volume we would estimate that eight of the larger four-beam-array systems could be built for a twenty percent increase in cost over Shiva. This laser would have the following properties:

- No. of Beams - 32
  Diameter - 30 cm
  Energy Stored - 60 MJ
  Glass Volume - 0.6 m^3

  Peak Power - 100 ps = 610 TW
  Efficiency - 0.1%

- Energy Out - 1 ns = 100 kJ
  Efficiency - 0.17%

The energy output for longer pulses (i.e. "several" nanoseconds) would be in excess of 150,000 J.

An alternative way to "eyeball" the costs would be to scale the costs as the capacitor bank and estimate that this system would cost approximately twice what the Shiva system would cost.

Reality is probably intermediate between these two estimates. The additional capacitor banks would cost about $4.5 M (at 25¢/J) and the additional complexity of the arrays might increase the engineering overhead. Offsetting factors would be the redundancy of components, i.e. one basic disc and flashlamp for all the amplifiers.

4.3 Overall Summary

Phosphate laser glasses appear to offer extreme benefit for the laser-fusion program in terms of an early test of the concept at a cost for the laser which will be much less than that identifiable with other approaches. The major points which have emerged from this study are:

- The economic advantages of keeping amplifier diameter below the parasitic limit are large for short pulses because the overall cost/TW will scale as $\alpha^2 n_0/n_2$.

- By use of the array concept it appears possible to observe parasitic restrictions and keep the number of beams which must be aligned on target down to a reasonable number.

- Implementation of the phosphate glass together with the array concept appears to offer a credible strategy of obtaining order of magnitude increase in the 100 ps output of glass-laser systems. For longer pulses the factor of improvement becomes smaller but appears to be a factor of two to three for nanosecond pulses.

- Neodymium-glass-laser systems producing peak powers of hundreds of terawatts in short pulses and more than 10^5 J in longer pulses appear feasible with an investment similar to the present ERDA investment in the LLL Shiva facility.

- Damage to dielectric coatings will shortly be a severe problem; the measured levels in the literature are lower than what state-of-the-art laser systems will be capable of achieving. Unless improved coatings exist the focusing optics will have to be much larger than the laser and hence more costly.

REFERENCES

1. N.L. Boling, A. Owyoung and A.J. Glass, UCRL 75628 (1974).
2. W.F. Krupke, IEEE J. Quantum Electron., QE-10, p. 450 (1974).
3. G. Leppelmeier, UCRL-50021-74 p. 68.
4. V.I. Bespalov and V.I. Talanov, JETP Lett. 3, 307 (1966).
5. B.R. Suydam, "Laser Induced Damage in Optical Materials," NBS Spec. Publ. 387, p. 42 (1973).
6. J.M. McMahon, Technical Digest of the Int'l Electron Devices Meeting (IEEE) p. 307 (1974).
7. E.S. Bliss, D.R. Speck, J.F. Holzrichter, J.H. Erkkila and A.J. Glass, Appl. Phys. Lett. 25, 448 (1974).
8. J.B. Trenholme, NRL Memorandum Report 2480 (July 1972).
9. J.M. McMahon, J.L. Emmett, J.F. Holzrichter and J.B. Trenholme, IEEE J. Quantum Electron., QE-9 (1973).
10. S. Guch, in UCRL-50021-4 p. 151 (1974).
11. ibid p. 154.
12. L.M. Franz and J.S. Nodvik, J. Appl. Phys. 34 p. 2346 (1963).
13. M. Weber et al., Opt. Commun. 18, p. 171 (1976).
14. J.M. McMahon, in Laser Induced Damage in Optical Materials: 1972, NBS Spec. Publ. 372, p. 100 (1972).
15. N.G. Basov et al., Lebedev Institute Preprint No. 74, Moscow (1976).
16. Private communication - D. Segawa, Hoya Optics, USA.
17. Private communication - J.B. Trenholme.
18. H. Kuroda, H. Masuko and S. Mackawa, Opt. Commun. 18, p. 169 (1976).
19. Hoya data sheets LHG-5
20. Private communication - J.L. Myers.

REFERENCES (cont.)

21. J. M. McMahon, Paper presented at IX IQEC, Amsterdam (1976).

22. R.L. Carmen, Plasma Physics Division Seminary (NRL) (May 1976).

23. D.K. Duston, "Factors Influencing the Gain in Neodymium Glass," Ph.D. Thesis Renassaler Polytechnic Inst., p. 125 (1969).

24. T.H. DeRieux and J.M. McMahon, "Damage in Laser Materials," NBS Special Publication 341, p. 19 (1970).

25. "Laser Program Annual Report 1974", UCRL-50021-74 pp. 271-273.

26. ibid p. 52.

27. Private communication - J.B. Trenholme.

28. "Laser Fusion Studies at NRL," NRL Memo Report 3315 pp. 9-10 (1976).

29. UCRL-50021-74, p. 40.

30. R.H. Lehmberg and J.M. McMahon, Appl. Phys. Lett. 28, p. 204 (1976).

31. J.M. McMahon, R.P. Burns and T.H. DeRieux, "Laser Induced Damage to Optical Materials," NBS special publication 414, p. 17 (1974).

32. G.W. Leppelmeier and M. Finklestein in "Laser Induced Damage in Optical Materials," NBS special publication 414, p. 48 (1974).

33. "Shiva Baseline Design", UCRL-50021-74, p. 79.

34. B.E. Newman, "Laser Induced Damage in Optical Materials," NBS special publication 414, p. 39 (1974).

APPENDIX A

Phosphate-Rod Systems

1. INTRODUCTION

The preceding study has focused on composite systems where the initial amplifiers are rod amplifiers and the final stage amplifiers are disc amplifiers. This choice was not explicitly justified at the time. In this appendix we will look at the expected efficiencies for systems composed only of rods. In the final analysis the question which must be addressed is whether or not this technology is scalable to the level of at least 10^{14} W or 10^{5} J which is expected to be necessary for critical tests of the laser fusion concept.

The scaling laws for long and short pulses will be the same as for disc amplifiers except that the nonlinear phase distortion factor n_2E^2 will be larger by a factor of $n_0 (\approx 1.52)$ in the case of a rod system which will lower the short-pulse intensity and efficiency by a similar factor.

2. PUMPING EFFICIENCY

A number of factors influence the pumping efficiency of laser amplifiers and careful evaluation is necessary to avoid errors in scaling these systems:

2.1 Surface Area to Volume Ratio

As disc amplifiers are scaled in size up to, but not above the parasitic limit (roughly $\alpha D_{major} = 2\ \alpha D = 3$) the ratio of volume of flashlamp plasma to laser glass volume remains constant and hence the gain can remain constant. As a rod is increased in diameter, however, the surface area to volume ratio decrease as D^{-1} and hence this geometrical constraint results in the efficiency (and cost effectiveness)

decreasing as D and for short pulses the efficiency (and cost effectiveness) decrease as D^2.

2.2 The Flashlamp Coupling Efficiency

For both rod[1] and disc amplifiers[2] has been experimentally verified to be sensitive to the solid angle of lamp radiation that the laser medium subtends. For flashlamps in the cases under consideration a relation which fits the available data is

$$\mathcal{E}_c = \left[\frac{D}{D_L}\right]^2 , \qquad \text{(A2.1)}$$

where D is the diameter of laser medium and D_L is the flashlamp mounting circle. Since the mounting circle can be no less than the rod diameter plus a flashlamp diameter d plus a mounting tolerance ($\mathcal{E}$), this factor can be written

$$\mathcal{E}_c = \frac{k}{\left(1 + \frac{d + \mathcal{E}}{D}\right)^2} . \qquad \text{(A2.2)}$$

This factor not only militates against very small amplifiers, but also is very important in comparing rod- and disc-amplifier pumping efficiency.

In an experiment at NRL several years ago a CGE-64 mm diameter rod amplifier was retrofitted with a 44 mm aperture set of discs in order to evaluate surface damage problems in a very clean environment. A raw evaluation of the pumping efficiency was performed at that time.[3] The flashlamp mounting circle (D_L) was equal to 95 mm in these experiments and the rod was surrounded by a water jacket such that the effective rod diameter as viewed from the lamp was 76 mm (the jacket diameter). In this case we would expect the relative coupling efficiency to be much better for the rod. The expected ratio for rod to disc efficiency from Eq. (A2.2) was:

$$\varepsilon_{rel} = \frac{76^2}{44} = 2.98 \ .$$

Measurements of the actual stored energy and efficiency:

For the 44 mm disc amplifier:

$$\begin{aligned}
\text{Measured gain} \quad & \alpha = .07 \text{ cm}^{-1} \\
\text{Stored energy} \quad & N = .5 \text{ J/cm}^3 \\
& V = 600 \text{ cm}^3 \\
& E_T = 300 \text{ J} \\
& \varepsilon = \frac{300}{80{,}000} = 0.375\%
\end{aligned}$$

For the 64 mm rod:

$$\begin{aligned}
\text{Measured gain} \quad & \alpha_M = .03 \text{ cm}^{-1} \\
\text{Stored energy} \quad & N = 0.214 \text{ J/cm}^3 \\
& V = 2000 \text{ cm}^3 \\
& E_T = 428 \text{ J} \\
& \varepsilon = \frac{429}{80{,}000} = .54\%
\end{aligned}$$

Hence, the measured relative efficiency was

$$\varepsilon_{rel} = 1.44 \ .$$

However, further study revealed that whisper modes were depleting the stored energy in the rod and that if these were stabilized the gain would have been .05 cm^{-1} on axis and .07 cm^{-1} at the periphery. The average-gain value (with parasitic stabilization) would have been $\bar{\alpha} = 0.6 \pm .005$ cm^{-1} and

$$\varepsilon_{rel} = 2.88 \pm 0.2 \ .$$

This experiment argues strongly in favor of this geometrical-coupling coefficient being the only real-efficiency factor which can strongly influence rod vs disc-pumping efficiency. For the 67 mm disc amplifiers which we saw earlier to be relatively optimal for phosphate glass the coupling factor; $\mathcal{E}_c = 0.48$.

Optimized rod amplifiers require a jacketing around them which suppresses whisper mode parasitics for $D > 1$ cm. Otherwise αD will limit at < 0.3 (and very inefficiently since the parasitic threshold is $\alpha D = 0.2$). Only one parasitic suppressing liquid which is stable and reasonably transparent for flashlamp light has ever been found, a $ZnC\ell_2$:H_2O solution with $SmC\ell_2$ additives[1]. All other known solutions exhibit excessive flashlamp absorption (or other vile properties). Even this liquid has some flashlamp absorption such that an optimum-layer thickness is 3 - 4 mm. With due allowance for the jacket wall the efficiency factor for optimized rods is

$$\mathcal{E}_c = \frac{(D_R + 1)^2}{(D_L)^2} .$$

For 14 mm o.d. lamps with a 3 mm radial clearance this factor becomes

$$\mathcal{E}_c = \left(\frac{D_R + 1}{D_R + 3} \right)^2 \quad (D_R \text{ in cm}); \qquad \text{(A2.3)}$$

The coupling factor will equal that for our optimum disc amplifier at $D_R = 3.6$ cm, larger rods will couple more efficiently, smaller rods less efficiently. This effect will modify the efficiency results given solely by the surface area to volume ratio.

2.3 Achievable Gain with Phosphate-Rod Amplifiers

To normalize rod performance to disc performance in either long- or short-pulse regime it is necessary to determine what value of the gain

coefficient can be achieved for different diameter laser rod amplifiers. The surface area to volume ratio constraint (discussed in Sec. A1) would predict αD = constant; in Sec. A2 we saw that this is too simple a picture. The geometrical efficiency increases for larger rods so we would expect that

$$\alpha D = (\text{constant}) \cdot \left(\frac{D+1}{D+3}\right)^2 . \qquad \text{(A2.4)}$$

There is a relevant datum to use in normalizing the equation, i.e., determining the value of the constant. Recently at LLL an optimized silicate-glass amplifier has been constructed.[4] This amplifier is optically pumped by linear flashlamps with reflectors shaped such that the radial gain profile is very flat; i.e., $\alpha(r) = \alpha_0 + \mathcal{E}(r)$; $\mathcal{E}(r) \ll \alpha_0$. This is important for amplifiers in large systems to minimize dynamic beam steering caused by the optical pumping. For large rods we will also see that parasitic constraints demand a flat profile to achieve maximum gain on axis.

This amplifier is also a good candidate for silicate normalization for other reasons. The gain coefficient is quite high (i.e., 10%/cm) compared to other amplifiers of similar size and the size (i.e., D = 40 mm) is quite close to the cross-over point in disc-rod geometrical pumping efficiency so it exists in an appropriate regime for normalization. From Eq. (A2.4)

$$(\text{constant}) = \frac{\alpha D}{\left(\frac{D+1}{D+3}\right)^2} = 0.8 ,$$

and

$$(\alpha D)_{\text{silicate}} = 0.8 \left(\frac{D+1}{D+3}\right)^2 . \qquad \text{(A2.5)}$$

For the silicate glasses even with the $ZnC\ell_2$ index-matching liquid there will be a limiting value of $(\alpha D) \approx 0.7$ above which the parasitic-whisper mode can no longer be suppressed because of residual index mismatch. There are other whisper modes involving paths partially in the jacket which can also enter at high αD values, but since $\alpha D \gtrsim 0.6$ only for $D \geq 12$ cm with silicate glass, parasitic modes are in practice a soluble problem with silicate glass.

For phosphate glass the achievable values of αD are not yet totally clear. If a phosphate rod were substituted for a silicate rod of equal doping in a laser head optimized for a flat-gain profile with silicate glass. The gain coefficient everywhere would be higher because we know from the disc laser tests that the net gain was higher by a factor of 2.2 showing not only the factor of 1.4 increase in the induced emission cross section but also an increase of a factor of 1.6 (= 2.2/1.4) in the energy stored as population inversion. The fraction of this increase in stored energy which represents a higher-absorption coefficient for flashlamp light will deoptimize the gain profile and cause a radial profile which increases towards the edge of the rod. Retaining the flat-radial-gain profile will then require lowering the doping by a factor of the relative-absorption strength. There are several possible causes of the higher absorption each of which could change the achievable-gain coefficient:

- All of the increased-energy storage is due to higher absorption. In this case the achieved-gain increase will be solely tracible to the increased cross section and

$$(\alpha D)_{\text{phosphate}} = 1.12 \left(\frac{D+1}{D+3}\right)^2 . \qquad \text{(A2.6)}$$

- None of the increase is caused by a higher absorption per ion. The quantum efficiency is higher by a factor of 1.6. In this case

$$(\alpha D)_{\text{phosphate}} = 1.76 \left(\frac{D + 1}{D + 3} \right)^2 . \qquad \text{(A2.7)}$$

- The most likely case might be that most of the increased absorption is caused by a larger absorption per ion, but the cross section is larger also. If we guess that the absorption per ion is 1.4 times stronger and the rest of the increase is caused by improved quantum efficiency. In this case

$$(\alpha D)_{\text{phosphate}} = 1.28 \left(\frac{D + 1}{D + 3} \right)^2 . \qquad \text{(A2.8)}$$

Figure A-1 shows αD as a function of D for silicate glass and what we feel is the most likely phosphate case.[3] It can be seen that $(\alpha D)_{\text{phosphate}}$ will exceed 0.6, the silicate-parasitic oscillation limit for diameters in excess of 48 mm.

It is not clear that the parasitic limit should be the same as for silicate glass because the passive-index match should be better for the lower-index-phosphate glass; indeed, in principle the index matching can be exact. In practice this may not be the case with rod amplifiers because the flashlamps will heat both the liquid and the laser rod and may cause dynamic loss of index matching. We can estimate this effect from silicate-rod results.

CGE has claimed that they have achieved $\alpha = .06\ \text{cm}^{-1}$ in a 9 cm rod amplifier (silicate glass).[5] This would place an upper bound of $\Delta n \leq -0.02$ due to thermal effects. With a phosphate glass the initial index of the solution can be set to be $\Delta n = +$ [illegible] relative to the rod. In the worst case then we would expect a thermal affect of $\Delta n = -.01$. This would lead to a parasitic threshold of $\alpha D = .87$ for this whisper mode.

However, this is not the only parasitic mode for rod amplifiers. There is another parasitic mode which will exhibit total internal reflection at the outside surface of the water jacket. Stabilization of this

mode requires an absorption in the mode path in the liquid jacket for 1.054 μm greater than the gain along the mode path in the laser rod. The best absorber will be Samarium in glass and/or the solution. However, this may force a $\Delta n \geq .01$ and will also absorb more pump radiation. We would estimate that αD will peak at $\sim 0.8 \pm .05$ for optimized-phosphate-rod systems.

An estimate on the achievable values of αD vs diameter including the effect of pumping losses associated with stabilizing this parasitic mode is shown in Fig. A.1 for the Kigre Q-88 phosphate glass. Figure A.2 replots this result in terms of gain vs diameter.

3. OPTIMUM-ROD SYSTEMS

We will consider both limiting cases, short pulses and long pulses and compare the performance of phosphate vs silicate glass in rods as well as in discs.

3.1 Figure of Merit - Short Pulses

Consider the following system; a cylinder of laser material pumped with a fixed amount of flashlamp energy per unit length. For a length Z of the material, the total pumping energy E_T is

$$E_T = E_p \cdot Z .$$

The required gain length can be defined by

$$I_f = I_o e^{\alpha Z} ,$$

where I_o and I_f are the initial and final laser intensities. Hence,

$$Z = \alpha^{-1} \ln \left(\frac{I_f}{I_o} \right) ,$$

and the total pump energy

$$E_T = \frac{E_p}{\alpha} \ln \left(\frac{I_f}{I_o} \right). \tag{A3.1}$$

Small scale self-focusing will limit the output intensity to a value less than that at which beam breakup occurs. This level will be

$$I_f \le C \cdot \frac{n_o \alpha}{n_2} ,$$

where C is essentially the spatial noise amplification factor.

The energy extraction from the amplifier, ΔE can be written as

$$\Delta E = C \Delta t \left(\frac{\alpha}{n_2} \right) \text{ for } I_o \ll I_f . \tag{A3.2}$$

From Eqs. (A3.1) and (A3.2) we can see that the overall efficiency of the amplifier will be:

$$\mathcal{E} = \frac{\Delta E}{E_T}$$

$$\mathcal{E} = \Delta t \left[\frac{C}{E_p} \right] \frac{\alpha^2}{n_2} \bar{n}_o \ln \left[\frac{I_f}{I_o} \right]^{-1} . \tag{A3.3}$$

To compare two different amplifiers operated with the same pump energy per unit length

$$R = \left(\frac{\alpha n_o}{n_2}\right)_1 \left(\frac{n_2}{\alpha n_o}\right)_2 \frac{\ln\left[I_f/I_o\right]_2}{\ln\left[I_f/I_o\right]_1} , \qquad (A3.4)$$

$$I_f(n) = C \frac{\alpha n_o(n)}{n_2(n)} ,$$

for $I_o \ll I_f$

$$R \simeq \frac{\alpha_1^2}{\alpha_2^2} \cdot \frac{n_2(2)}{n_2(1)} \frac{n_o(1)}{n_o(2)} . \qquad (A3.5)$$

To compare silicate glass with phosphate glass it is necessary to note that parasitic effects will limit large amplifiers and that the achievable gain for smaller rods will be smaller than found in disc experiments (i.e., $\alpha_{rel} \sim 1.6$ rather than 2.2). The relative efficiency ratio will change with the amplifier diameter. For example:

Small rods ($\sim$ 4 cm) R = 3
Larger rods ($\sim$ 12 cm) R = 2.07

By comparison, the figure for a disc configuration is R = 5.1 in terms of a phosphate to silicate-improvement factor.

If we wish to compare the relative efficiencies of phosphate-rod amplifiers vs phosphate-disc amplifiers we must note that:

- In the case of a disc amplifier, the phase distortion is reduced by a factor n_o(= 1.52) more than in the rod case.
- The pumping efficiency and hence E_p for rods will vary with diameter and so will the gain coefficient.

An expression for the relative efficiency of a rod amplifier to a disc amplifier then would be

$$R(0) = \frac{\mathcal{E}_{rod}}{\mathcal{E}_{disc}} = \frac{1}{1.52} \frac{E_p(\text{disc})}{E_p(\text{rod})} \frac{\alpha^2(D)\text{rod}}{\alpha^2 \text{ disc}} . \tag{A3.6}$$

We can evaluate the relative pump energy; as noted before (Sec. 2) for our disc amplifiers this factor is 0.43, for rod amplifiers we can use Eq. (A2.3)

$$E_p(\text{rod}) = k \left(\frac{D + 1}{D + 3}\right)^2 , \tag{A3.7}$$

we can also evaluate the gain from Eq. (A2.8) in the parasitic-free case to find

$$R(D) = \frac{0.735}{D^2} \left(\frac{D + 1}{D + 3}\right)^6 \times 10^2 . \tag{A3.8}$$

Actually parasitics will make large rod systems less optimal than indicated by Eq. (A3.8). Figure A.3 shows the relative cost of rod vs disc systems for generating short pulses.

It can be seen that the crossover in favor of rods only occurs for very small systems, i.e., less than 14 mm in diameter. This would not appear too realistic for a large system, however, since at 100 ps the amplifier output would only be about 5 J and a 100 TW laser would require ~ 2000 parallel-final amplifiers.

For larger rods the overall efficiency quickly become prohibitively low compared to disc systems. For short pulses one cannot simply reduce the number of beams by going to larger diameter rods because the extraction efficiency roll off is so rapid. In Fig. A.4 the total power per beam is computed to illustrate this point.* Even the large and very

---

*The assumption here is that the B integral is allowed to reach B = 7.5; no B integral contribution for polarizers, isolators or the like is included hence, the numbers are probably optimistic by 20 - 30% (cf Sec. 3 of main report) but they illustrate the performance of rods of different diameters.

inefficient 12 cm amplifier can only reach about 2/3 of the output of the much smaller disc systems at an expected cost seven times as high.

In summary, in all cases rod systems appear much less attractive than disc systems because for practical size amplifiers not only will the laser cost be higher by a large factor ($\simeq 3 - 6$) but the number of beams necessary to reach some given total power will be larger by system.

3.2 Figure of Merit - Long Pulses

For long-pulse operation where self-focusing is not a limitation we would expect the phosphate glass to perform better than the silicate because the energy storage is better. As we saw before, there is not a unique figure of merit here, rather it varies with initial and final loadings. For purposes of a meaningful comparison let us compare the efficiencies of amplifiers which have an input pulse of energy density E_o and an output pulse of energy $E_f = 4\ \mathrm{J/cm^2}$. The length of medium required for the pulse amplification can be found by integrating the Franz-Nodvik expression for this intensity.[6] The result is:

$$\frac{E_f}{E_s} = \ln\left[1 - (1 - \exp E_o/E_s)e^{\alpha Z}\right] .$$

The length Z is inversely proportioned to the overall extraction efficiency; hence, the efficiency

$$\mathcal{E} = \frac{(\text{const.}) \cdot \alpha}{\ln\left(e^{E_f/E_s} - 1\right) - \ln\left(e^{E_o/E_s} - 1\right)} .$$

To compare silicate and phosphate glass we need to take a realistic case as the figure of merit will vary depending on E_o as well as E_f and the gains will vary as a function of diameter.

For the initial conditions E_o - $.4\ \mathrm{J/cm^2}$ and $E_f = 4\ \mathrm{J/cm^2}$, the relative efficiency of phosphate vs silicate-glass amplifiers.

$$\mathcal{E}_{rel} = (0.91) \frac{\alpha \text{ phosphate } (D)}{\alpha \text{ silicate } (D)} .$$

If we examine Fig. A.2 for the variation of α with diameter for silicate and phosphate glass we see that for small rods ($D \leq 4$ cm) the overall efficiency figure for phosphate vs silicate is

$$\mathcal{E} \approx 1.45 .$$

For large rods, however, the parasitic problem becomes increasingly worse until at 12 cm the relative efficiency $\mathcal{E} \approx 1.25$.

In comparing rods to disc amplifiers it is necessary to account for the fact that the pumping efficiency of rods will increase as our diameter increases.

$$\mathcal{E}\left(\frac{\text{disc}}{\text{rod}}\right) = \frac{\alpha(\text{disc})}{\alpha(D)\ (\text{rod})} \cdot (\text{relative coupling efficiency})$$

$$= \frac{\alpha(\text{disc})}{\alpha(D)\ (\text{rod})} \cdot 0.48 \left(\frac{D+3}{D+1}\right)^2 .$$

At 4 cm diameter

$$\mathcal{E}_{d/r} = 1.09 .$$

At 8 cm diameter

$$\mathcal{E}_{d/r} = 1.33 ,$$

and at 12 cm diameter

$$\mathcal{E}_{d/r} = 1.65 .$$

Unlike the short-pulse case, in this case there is no cross-over: the disc amplifier behaves more efficiently at any diameter. The margin

of superiority is, however, less dramatic than in short-pulse cases.

3.3 Fluorophosphate-Rod Amplifiers

A similar analysis can be performed for fluorophosphate glasses, such as FK-51 where the gain coefficient is essentially the same as for silicate glass but the n_2 coefficient is smaller by a factor of 2 (0.7×10^{-13} esu vs 1.4×10^{-13} esu).

The results are shown in Figs. A.3 and A.4. Fluorophosphate amplifiers are less efficient than phosphate amplifiers by a significant factor, 1.7 for short pulses, the cross over with phosphate-disc amplifiers occurs at an even smaller diameter - 1 cm and in most cases the peak power per beam is essentially the same as the phosphate or only marginally higher (~ 10%) for large rods.

For long pulses the fluorophosphate will behave similarly to the silicate glass, i.e. lower by a factor of 1.25 to 1.45 depending on diameter than the phosphate.

4. OVERALL ASSESSMENT - RODS VS DISCS

The two cases we have examined have been extreme examples. In both of them the phosphate-disc amplifier was markedly superior to a phosphate-rod system.

If we examine the real question of which type of system is more optimal for a large system to do laser fusion experiments the answer becomes clear. The best rod system would have final amplifiers 10 ± 1 cm in diameter and would be aimed at producing nanosecond or longer pulses. Some fraction of the inherent 40% increase in price over a disc system of similar nanosecond capability might be considered an investment in a system which would be simpler and cheaper to operate. However, if the experiments demanded short pulses this system could not deliver them except at greatly reduced output. The disc system can deliver 4 J/cm^2 average for pulses as short as 250 ps. A 10 cm rod system is limited to pulses no shorter than 500 ps at 4 J/cm^2.

In short the intuitive appeal of rod system is not merited when examined closely for the laser fusion application. In no case which is

even remotely useful for laser fusion will their performance surpass that of reasonably optimized disc lasers; indeed in cases which seem reasonably realistic for pellet experiments the overall cost will be higher by a factor of two or more than a disc-laser system and the complexity will be at least equivalent.

REFERENCES (Appendix A)

1. J.M. McMahon, R.P. Burns, and T.H. DeRieux, "Suppression of Parasitic Oscillation in Laser Rod Amplifiers," NBS Spec. Publ. 414, p. 17 (1974).

2. Laser Fusion Studies at NRL, NRL Report 7838, pp. 36-37 (Oct. 1974).

3. J.M. McMahon, O.C. Barr and R.P. Burns, "A Helically Pumped Disc Laser Amplifier," 1973 Int. Electron Devices Meeting Technical Digest, p. 568 (Dec. 5, 1973).

4. G.J. Linford and S.M. Yarema, Lawrence Livermore Laboratory Preprint UCRL-78579 (1976).

5. CILAS Data Sheet, "Technical Characteristics of the B64A3 and B90A3 Laser Amplifier Heads" (1976).

6. L.M. Franz and J.S. Nodvik, "Theory of Pulse Propagation in a Laser Amplifier," JAP. 34, 8, p. 2346 (1963).

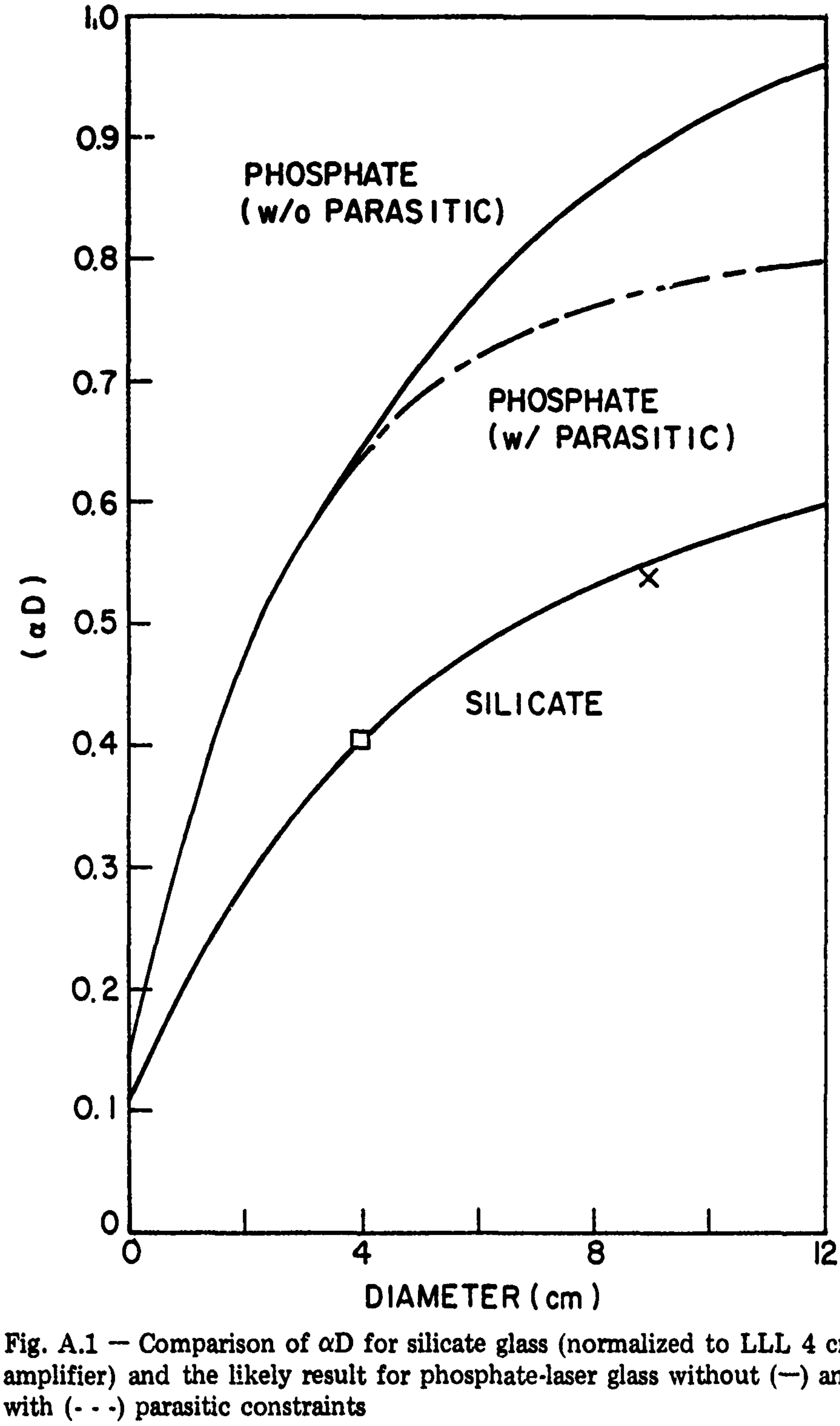

Fig. A.1 — Comparison of αD for silicate glass (normalized to LLL 4 cm amplifier) and the likely result for phosphate-laser glass without (—) and with (- - -) parasitic constraints

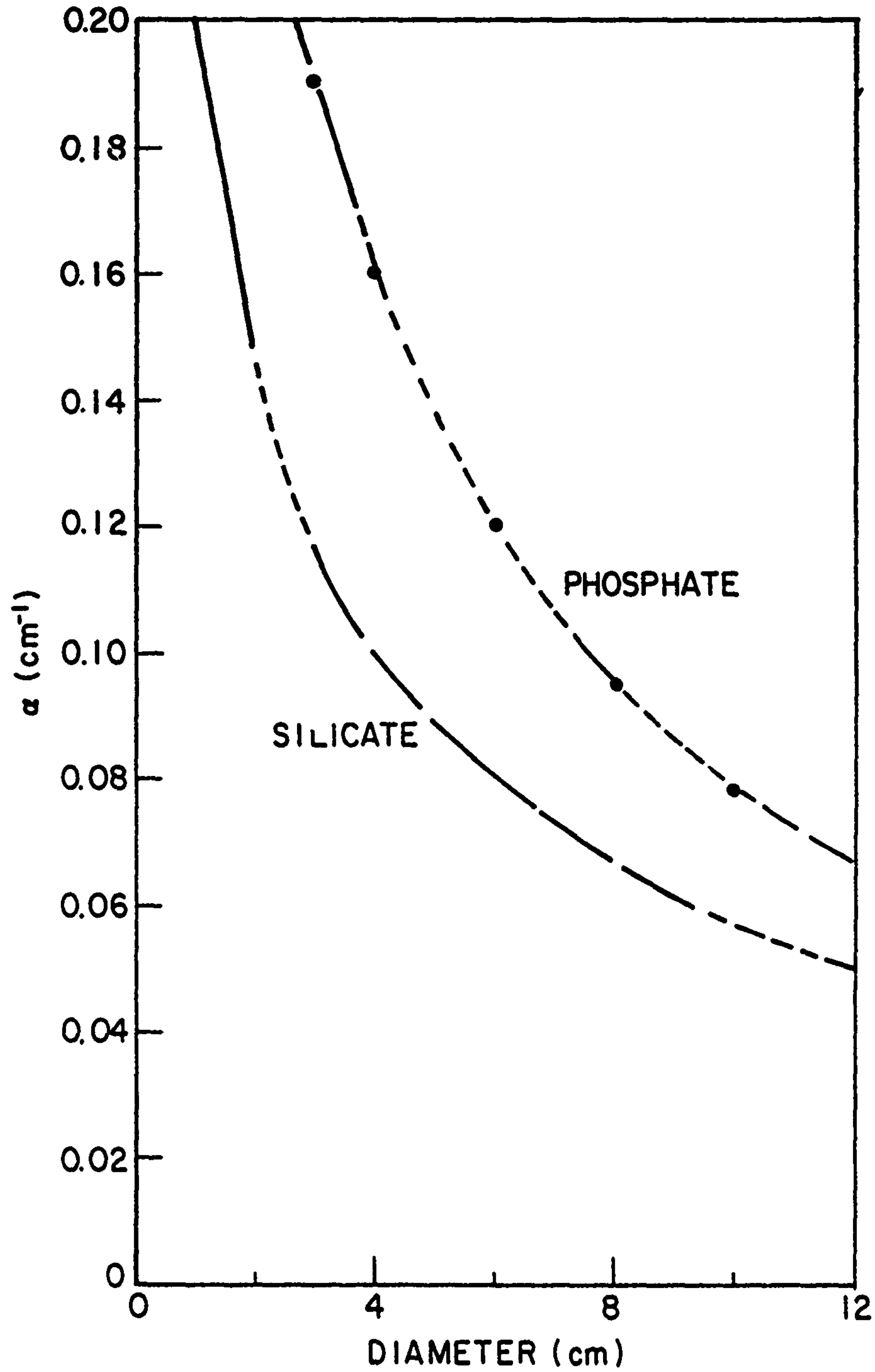

Fig. A.2 — α vs D for phosphate and silicate laser glass

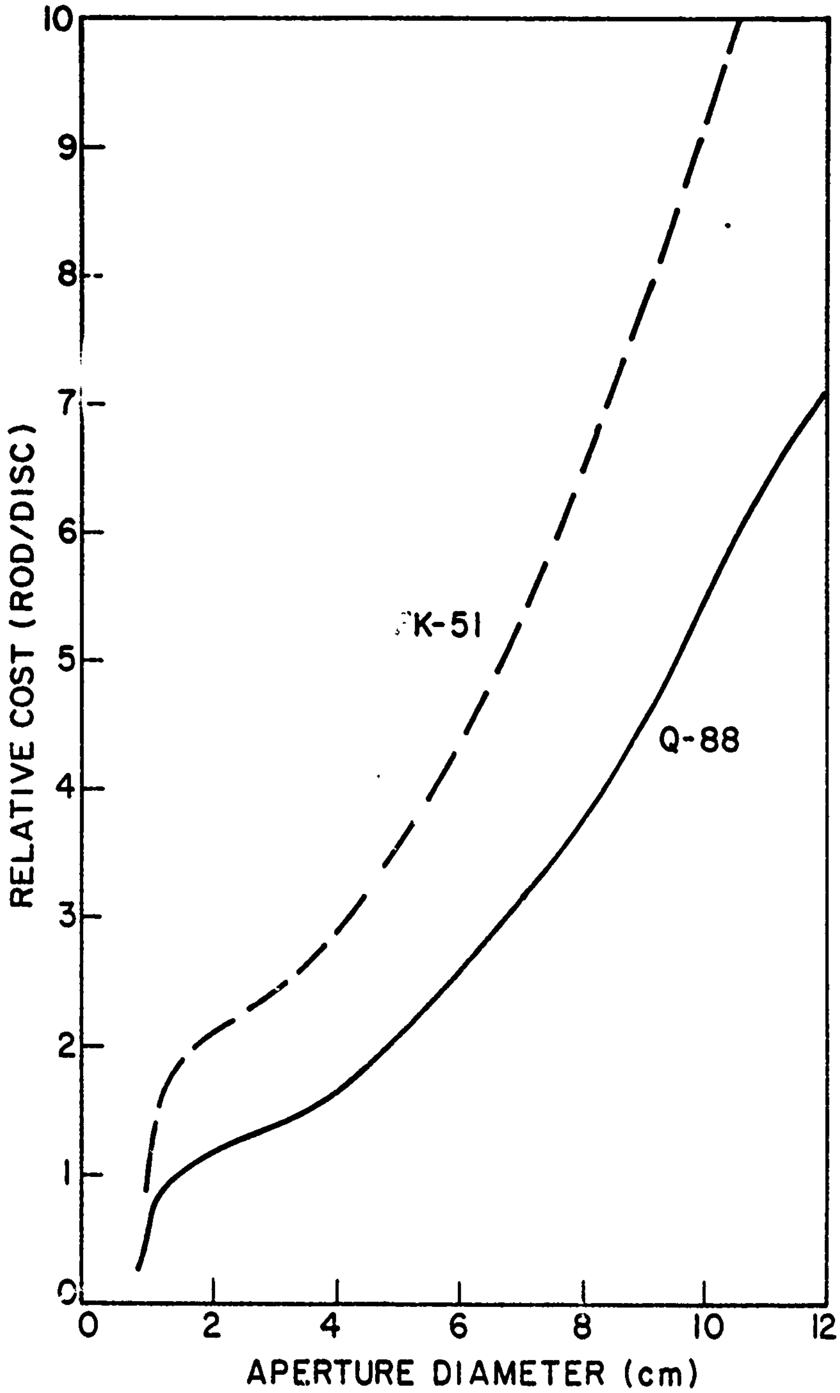

Fig. A.3 — Relative cost for rod vs disc amplifiers in short-pulse limit as a function of diameter for phosphate and fluorophosphate laser glass

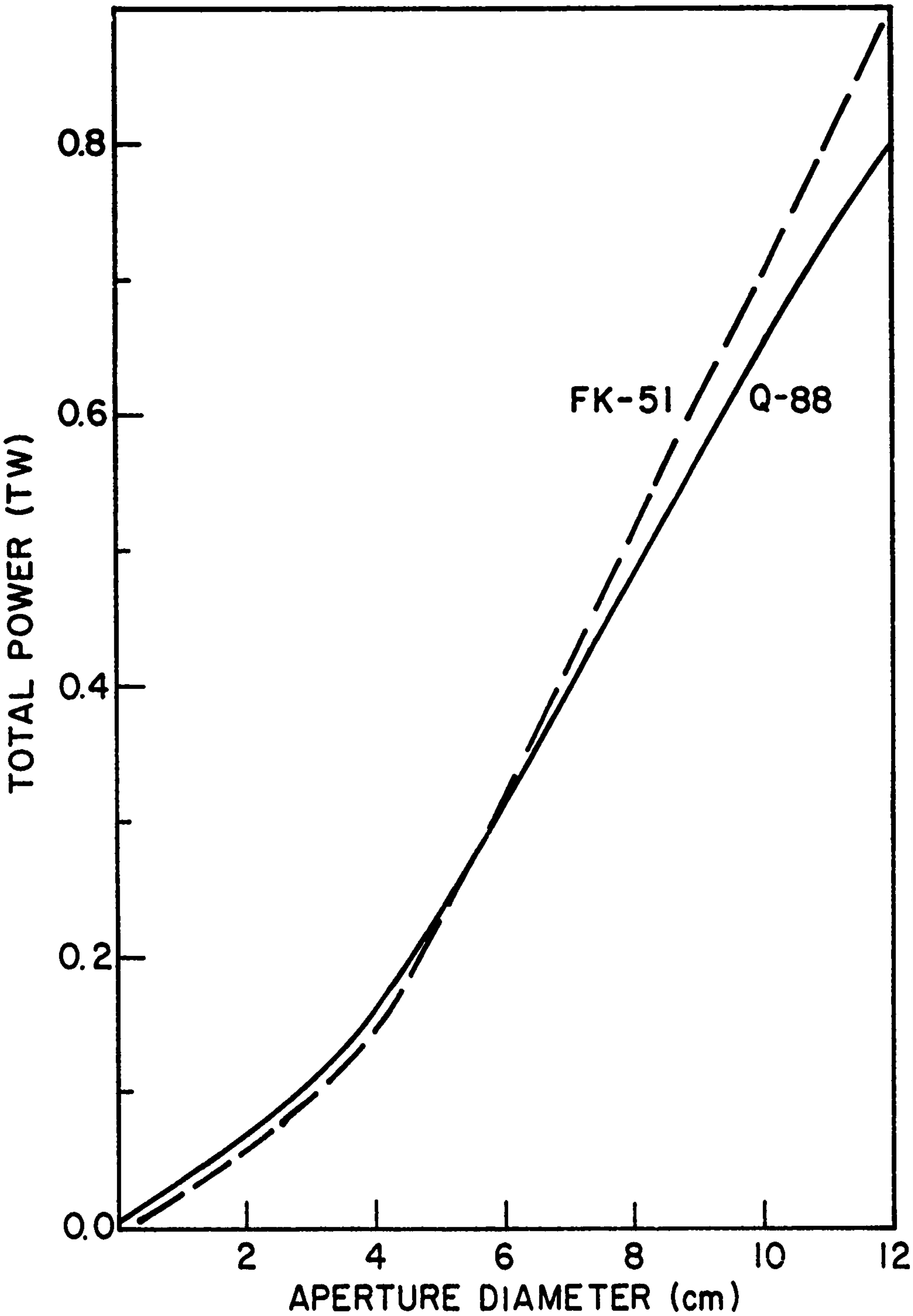

Fig. A.4 — Peak-power capability (in TW) for phosphate-rod amplifiers and FK-51 fluorophosphate rod amplifiers. Normalization is relative to NRL (or LLL) silicate results.

APPENDIX B

Amplifier Calculations

To calculate the expected amplifier performance exactly it is necessary to account for the nonuniform radial beam profile. This cannot readily be done analytically as the integral will have the form of

$$E_T = E_s \int_0^{2\pi} d\theta \int_0^R r dr \, \ell n \left[1 + \left(\exp\left(\frac{\mathcal{E}_o(r, \theta)}{\mathcal{E}_s} \right) - 1 \right) e^{\alpha Z} \right] .$$

This integral in general can only be evaluated by numerical methods for desirable beam profiles. While possible this procedure is not quick and may give erroneous results due to mensuration errors.

We will pursue an alternate approach whose justification is solely that over the parameter range of interest it gives the saturation behavior correctly enough to expect a precision of better than 10% over the range of interest.

Figure B.1 shows measurements on the original NRL disc amplifier of output energy vs input energy with the same spatial profile as we are now using. We can fit the equation

$$\frac{E_f}{E_s} = \ell n \left[1 + \left(\exp\left(\frac{E_o}{E_s} \right) - 1 \right) e^{\alpha Z} \right]$$

to these results by adjusting the value of E_s to give the best fit.

If we define E_f and E_o as the total energy divided by the area

$$E = \frac{E_T}{A} .$$

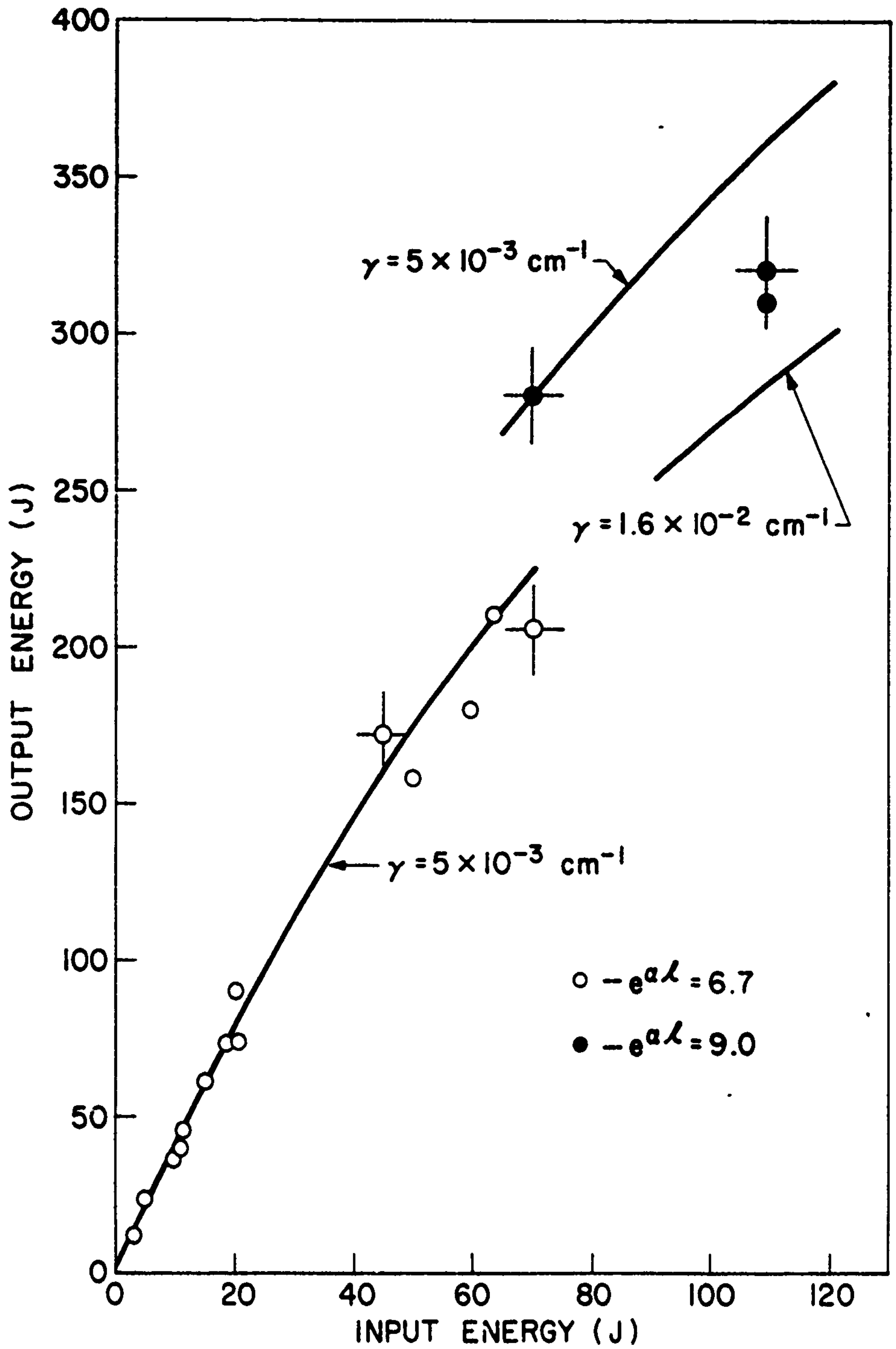

Fig. B.1 — Experimental results obtained on prototype NRL disc laser with a similar spatial profile to what is presently used

The best fit for silicate glass was found for $E_s = 5.1\ J/cm^2$; i.e. a factor of 1.58 more than the real saturation flux. The fit is excellent for outputs up to ~300 J and as low as 50 J. For the phosphate calculations a saturation flux larger by a factor of 1.58 was also assumed, i.e. $3.54\ J/cm^2$ for Q-88 laser glass.